Context-aware System Service Call-oriented Symbolic Execution of Android Framework with Application to Exploit Generation

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Abstract—Android Framework is a layer of software that exists in every Android system managing resources of all Android apps. A vulnerability in Android Framework can lead to severe hacks, such as destroying user data and leaking private information. With tens of millions of Android devices unpatched due to Android fragmentation, vulnerabilities in Android Framework certainly attract attackers to exploit them. So far, enormous manual effort is needed to craft such exploits. To our knowledge, no research has been done on automatic generation of exploits that take advantage of Android Framework vulnerabilities. We make a first step towards this goal by applying symbolic execution of Android Framework to finding bugs and generating exploits. Several challenges have been raised by the task. (1) The information of an app flows to Android Framework in multiple intricate steps, making it difficult to identify symbolic inputs. (2) Android Framework has a complex initialization phase, which exacerbates the state space explosion problem. (3) A straightforward design that builds the symbolic executor as a layer inside the Android system will not work well: not only does the implementation need to be maintained whenever Android gets updated. We present novel ideas and techniques to resolve the challenges, and have built the first system for symbolic execution of Android Framework. It fundamentally changes the state of the art in exploit generation on the Android system, and has been applied to constructing new techniques for finding vulnerabilities.

I. INTRODUCTION

Android Framework (aka, Android Application Framework) contains a set of system services, managing system resources and life cycles of applications [23]. Recently, many vulnerabilities in Android Framework have been identified [15], [16], [18], [17]. Vulnerabilities in Android Framework can cause severe security consequences; e.g., malicious apps can exploit them to steal user passwords, take pictures in the background, launch UI spoofing attacks, and tamper with user data [36], [39], [40]. On the other hand, due to Android fragmentation among the 1.4 billion active devices [42], tens of millions of Android devices are left unpatched, “turning devices into a toxic hellstew of vulnerabilities” [1]. Given the severe security consequences and the large number of vulnerable Android devices, attackers are certainly motivated to exploit Android Framework vulnerabilities.

So far, such exploits have been mainly crafted manually; attackers need to go through the complex logic of Android Framework to figure out the exploit, which is a challenging, laborious, and lengthy process. Previous researches have shown the feasibility of automatic exploit generation, but mostly deem Windows or Unix stand-alone executables to be victims [7], [6]. (Certainly, once an exploit succeeds, e.g., in hijacking the control flow of the victim executable, the payload may further target other victims; how to construct a payload is beyond the scope of this paper.)

There has been no previous work that automatically generates exploits taking advantage of Android Framework vulnerabilities. Such an exploit is embedded inside a malicious app and may target another app. The exploit generation thus has to consider multiple entities: the malicious app, the system services in Android Framework, and the victim app. For example, in order to launch a task hijacking attack [36], which seeks to place a malicious activity in the back stack where the victim activity resides, the malicious app invokes the Activity Manager Service, which further communicates with a set of other system services and finally adds the malicious activity to the back stack hosting the victim activity. A new family of Android Framework specific problems have to be investigated and dealt with, e.g., how to handle the interaction between system services, how the states of apps are represented in Android Framework. Therefore, it will not work out by porting an existing exploit generation system that targets stand-alone executables to Android for exploit generation.

In addition, existing techniques typically generate exploits as some simple form of inputs of stand-alone executables, such as a command line argument, a format string, a network packet, exceptions exist; e.g., fuzzing has been used for revealing input validation bugs in Android Framework [31], [11]; the bug-revealing inputs can be used to launch DoS attacks trivially. We consider general types of vulnerabilities. The malicious activity can then be used to conduct, e.g., UI spoofing.

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a piece of file metadata, etc. In contrast, the exploit we consider here is part of a malicious app, and comprises the malicious app’s configuration (i.e., the manifest file) and code that issues system service calls. This is another reason why existing exploit generation techniques are not applicable here.

This work aims at automatic generation of exploits that take advantage of Android Framework vulnerabilities. It has multiple security implications. First, it advances the state of the art in exploit generation on the Android system, and upgrades attackers’ capabilities of crafting zero-day exploits. With the large number of automatically generated exploits, even after an exploit is well known and suppressed, it will be trivial for attackers to roll out fresh exploits. This calls for a better understanding of attackers’ capabilities and more powerful defense against such exploits. Second, it can be applied to defense systems. For instance, the generated exploits can be fed into automated malware signature generation algorithms by defenders without seeing real-life malware [6], [14]. Third, as shown in our evaluation, the techniques proposed in this work can be used to find Android Framework vulnerabilities.

An Android Framework vulnerability is exploited usually because some security property $P_s$ is violated. For example, a vulnerability due to insufficient permission checking is exploited if the property that “the target resource can only be accessed with proper permission” is violated; a task hijacking attack succeeds when the security property that “the malicious activity should not be placed onto the back stack hosting the victim activity” is broken. Thus, among all possible execution paths (of Android Framework), we apply symbolic execution to searching for paths where a given $P_s$ can be violated; if such a path exists, a suspected vulnerability is found and the corresponding path condition may be used to construct exploits. The exploits then can be used to validate the suspected vulnerability.

**Challenges** Several challenges are raised by symbolic execution of Android Framework for exploit generation.

First, Android Framework hosts a set of system services serving all apps; thus, it has a large number of data structures that store the information of the different entities (system services and apps), e.g., a list that stores the permissions granted to the installed apps, and stacks that store activities of different apps. From the perspective of exploit generation, a vital step is to correctly identify which variables are derived from the malicious app and specify them as symbolic inputs (since this means the variables may be manipulable by attackers), such that all possible values of these variables can be considered by path exploration. However, it is challenging to determine, among the numerous variables in Android Framework, which have been derived from the malicious app. Previous work [19], [4] applies tainting to revealing whether taints originated from specific sources (e.g., return values of some system calls in the app) may propagate to specific sinks. But no previous work has been done for comprehensively tracking the information flow from a whole app to the underlying system services. Such tracking is very difficult, if not impossible, as the information spreads throughout app installation, system service initialization, and starting the app. Considering the complexity of these steps, a precise tainting is very hard to achieve, as it requires enormous work for handling overtainting and undertainting [37].

This is a unique challenge, because, as aforementioned, previous exploit generation techniques usually create exploits as a simple form of inputs, and the variables corresponding to the inputs, such as a command line argument and a network packet, are easy to identify. But the exploit we consider here is part of an app comprising configuration and code, and the information flow from the app to Android Framework is complex. This renders the identification of symbolic inputs difficult.

Second, as Android Framework has a very complex initialization phase, the whole-program symbolic execution that starts from the main function of Android Framework can lead to severe state space explosion. An alternative to the whole-program symbolic execution is under-constrained symbolic execution [34], [20], [35], which can start from an arbitrary function within the program and thus allows previously-unreachable code to be checked. Nevertheless, as it skips the initialization phase, the execution context (e.g., the type and value information of variables) that could have been provided by the initialization is missing. For example, consider a virtual function call $r$.foo, where $r$ is a reference of an interface or abstract class type; as the real type of the object pointed to by $r$ is unknown, path exploration virtually considers $r$ as a symbolic input and has to explore each of the possible dispatch targets of the call, while only one target would be explored if the type information were provided. This causes many spurious paths to be explored, and even renders the symbolic execution of programs that contain many virtual function calls intractable.

Previous work seeks to resolve this problem by running concrete execution first and then switching to symbolic execution when, e.g., some function of interest is invoked [32]. It utilizes the execution context generated by concrete execution for symbolic execution, which is a promising direction. Nevertheless, the path exploration is severely limited in the previous work, because all variables inside the context are regarded as concrete inputs (even though some of them should be symbolic inputs); we call it over-constrained symbolic execution. How to properly leverage concrete execution for symbolic execution is still an open research problem.

Third, to implement the symbolic executor, a straightforward design is to place it inside the Android system. But this way the symbolic executor is tightly coupled with Android. The implementation has to handle compatibility with the components of the Android system, such as the Android Runtime (ART). This significantly complicates the implementation. Moreover, whenever the Android system is updated, the implementation has to be maintained. To avoid the complicated implementation and endless maintenance, a decoupled architecture is needed.

Finally, in order to implement an exploit generation system, a large number of engineering issues have to be addressed. For example, it has to handle class loading and system bootstrapping, deal with the inter-service communication and calls to native code, and construct exploits using path conditions. The process of addressing these engineering issues involves much innovation as well as tremendous effort.

**Approaches** Instead of tracking how variables are derived from a malicious app, we seek to identify them by monitoring how they are used. Based on the insight into the patterns how variables in Android Framework are accessed, we propose slim tainting to capture the access to variables derived from the
malicious app and identify them as symbolic inputs precisely. Compared to conventional tainting that usually requires significant manual effort to handle overtainting and undertainting, the slim tainting is automatic and precise (Section IV).

We run the initialization phase of Android Framework as whole-program concrete execution, and then perform symbolic execution under the context provided by the initialization phase. This is based on the observation of Android Framework that it consists of the initialization phase and then the ready-for-use phase, and the initialization phase is fairly stable among different runs as long as the system configuration does not vary. The combination of concrete and symbolic executions avoids the state space explosion due to the complex initialization and meanwhile does not lose the execution context (Section III). To avoid over-constrained symbolic execution, in the execution context provided by the concrete execution, variables derived from the malicious app are identified by weaving slim tainting into symbolic execution, such that these variables are specified as symbolic inputs just in time during symbolic execution.

An architecture that puts the symbolic executor into the Android system leads to a coupled implementation. In contrast, the symbolic executor in our design is placed out of the Android system, implemented in a way independent from the Android system components. The novel architecture allows concrete execution to be run on Android and symbolic execution on the independent symbolic executor. Now, the problem is reduced to how the symbolic executor recognizes the information in the execution context provided by concrete execution (Section V).

We have overcome the scientific and engineering challenges, and implemented the system named CENTAUR. We utilize CENTAUR to construct new bug finding techniques. Given a security property $P_s$, CENTAUR automatically finds possible paths in Android Framework where $P_s$ may be violated: the violation of $P_s$ is represented as a constraint added to each path condition, and if the augmented path condition is resolvable, a possible vulnerability is found. The new bug finding techniques are automatic and guarantee zero false positives, in contrast with recent research on finding Android Framework bugs that requires laborious and error-prone manual work [39], [36]. Besides, CENTAUR generates hundreds of exploits in minutes, and the exploits are verified on different versions of Android systems. We report our new findings on bugs, exploiting conditions, and more accurate vulnerability description.

- CENTAUR is the first system that performs automatic generation of exploits that take advantage of Android Framework vulnerabilities, and the first system that supports symbolic execution of Android Framework. It significantly changes the state of the art in finding Android Framework bugs and exploiting them.
- Unique challenges that cannot be resolved by existing symbolic execution techniques have been identified; specifically, how to identify symbolic inputs given a complex information flow from an app, how to leverage concrete execution without leading to over-constrained symbolic execution, and how to design a symbolic executor decoupled from the target system.
- We present novel ideas and techniques to address the challenges in the context of Android Framework, such as a new approach to combining concrete execution and symbolic execution, and an architecture that decouples the symbolic executor from the target system.
- We have implemented CENTAUR after overcoming many research and engineering challenges, and evaluated it in terms of effectiveness and precision.

II. BACKGROUND AND OVERVIEW

A. Background

Android Framework provides a collection of system services, which implements the fundamental features within Android, such as managing the life cycle of all apps, organizing activities into tasks, and managing app packages. Most of the system services, except for the media services, run as threads in the System Server process [23]. Thus, the System Server process plays a central role in Android Framework. This work uses the services in this process as examples to illustrate the ideas and techniques, which should be applicable to other services.

A service exposes service interfaces, which are APIs invocable from apps, by declaring them in an Android Interface Definition Language (AIDL) file [2]. When an app invokes a service API, the call is passed through the IPC mechanism Binder and handled by the process hosting the service.

B. Overview

Given a specific security property $P_s$, a malicious app invokes one of the service interfaces to drive the Android Framework execution to violate $P_s$. Therefore, exploit generation leads to three questions: Which service interfaces should be invoked? What conditions in terms of the parameter values and the app configuration should be satisfied, such that the invocation leads to a successful exploitation? How to build a malicious app based on the conditions? The questions are resolved by the following three steps, respectively.

The service interface method that should be invoked to launch an attack is called the attack’s entrypoint service interface. Given $P_s$, it is usually straightforward to determine the entrypoint service interface for launching the attack. For example, if the violation of $P_s$ refers to that a service interface method accesses some resource without sufficient permissions, then this service interface is the entrypoint one. In addition to making using of API specification and expert knowledge, static analysis can also be used to determine the entrypoint. For example, assume that a DoS attack is launched by raising unhandled exceptions from some internal method, then service interfaces that can reach the internal method are entrypoints. Thus, the selection of the entrypoint mainly depends on the attack, and we will discuss this step when concrete attacks are considered in the evaluation (Section VII). We do not bind our system to any specific selection methods. The second step is to obtain the app configuration values and the parameter values used to invoke the entrypoint service interface. Our approach is to utilize symbolic execution to find such input values, which is the focus of this paper. Finally, the values obtained at the second step are used to build exploits. Our evaluation demonstrates how to build exploits from the values.

Figure 1 shows the architecture of CENTAUR. At its core is the symbolic execution engine, which performs symbolic execution of Android Framework. The output is used to build
exploits. Between the engine and the Android system is the execution context query server, which migrates the execution context information from Android to the engine. The details will be described in the following sections.

C. Skeleton Malicious App

There is a dilemma that we are in the process of completing a malicious app, while the malicious app has to get launched so that we can identify variables in Android Framework derived from the app. But how to launch a malicious app that has not been completed? Our insight is that, due to the nature of symbolic execution, the concrete values of symbolic inputs do not matter (detailed in Section IV); hence, a skeleton malicious app (skeleton app, for short) that works as a placeholder suffices. The skeleton app can be an app selected to carry the exploit. We assume that the skeleton app is specified or provided by users of our system (i.e., malware developers). Or, for security analysts’ purpose, it can be one that contains all the aspects of a regular app, including the manifest file, activities, and services, but does not implement any essential functionality; in particular, the skeleton app used in our experiments borrows the manifest file from the Android developer website, which has “every element that it can contain” [3].

III. COMBINING CONCRETE & SYMBOLIC EXECUTIONS

A. Missing Execution Context

Android Framework has a complex initialization phase before system services are ready for use. However, symbolic execution suffers from the path explosion problem, as the number of distinct execution paths is often exponential in the number of branches. Thus, symbolic execution starting from the program entry of Android Framework SystemServer.main probably fails to finish the initialization phase. Besides, the initialization creates multiple threads for running services, which also complicates the symbolic execution. Therefore, symbolic execution that can skip the complex initialization phase is desirable.

**Definition 1:** An execution context consists of the program counter, register file, stack, and heap. For a Java program, the heap is a collection of classes and objects.

Under-constrained symbolic execution can directly start from an arbitrary function within a program [34]. As it effectively skips the costly initialization phase, this approach reduces the number and length of execution paths to be explored. However, due to skipping the functions in the path prefix, the execution context for symbolic execution is missing. Specifically, the type and value information of the input variables, i.e., non-locally defined variables read during symbolic execution, is lost. It causes several problems.

First, without the type information, it is hard to determine the dispatch target of a virtual function call. Consider an example `s.iterator()`, where `s` is a reference of the `Set` interface type. But `Set` is implemented by over 40 subclasses in Android Framework code, which means that symbolic execution needs to try each possibility, causing many spurious paths to be explored. Note that such virtual function calls prevail in Android Framework.

Second, due to the lack of the value information of variables, it is unknown how to handle instructions or function calls that involve them. For example, consider `LocationManagerService.mProviders`, which is an `ArrayList` that stores currently installed GPS providers; as the elements and the length of the `ArrayList` are unknown, it is hard to carry out a loop that iterates through the list. One workaround is to regard the list as a symbolic input and then handle it using lazy initialization [28]; this way, however, the loop becomes unbounded and elements of the list become symbolic, which exacerbates the path explosion problem.

B. Solution

Our observation of Android Framework is that its execution consists of the initialization phase and the ready-for-use phase, and the initialization phase is fairly stable among different runs, since the system boots according to the system configuration and the currently installed apps, which are stable. We thus run the initialization phase as whole-program concrete execution, and then perform symbolic execution starting at the entrypoint service interface method under the execution context provided by the concrete execution. It is notable that the type and value information of all the variables is available, which directly resolves the issues discussed in Section III-A. The combination of concrete and symbolic executions avoids the state space explosion due to the complex initialization, and meanwhile preserves the execution context for symbolic execution.

For the purpose of exploit generation, the initialization phase refers to both the system initialization and the initialization of the skeleton malicious app until it is ready to make calls to the entrypoint service interface method, such that Android Framework has all the variables derived from the skeleton app that can possibly be used by the service interface call.

However, the concrete execution leaves an execution context where every variable is concrete, including those derived from the skeleton app. How to perform symbolic execution in this situation? Previous work that switches from concrete execution to symbolic execution simply uses the concrete values of the variables in the execution context and only considers the parameters of the function-under-test as symbolic inputs [32], which severely limits path exploration and leads to over-constrained symbolic execution. Unlike the previous work, we
identify variables derived from the skeleton app as symbolic inputs, such that the path exploration considers all possible values of the variables, as presented in the next section.

IV. IDENTIFYING SYMBOLIC INPUTS

When symbolic execution is applied to exploit generation targeting stand-alone executables, the form of exploits is usually simple, e.g., the SQL query string used to launch SQL injection attacks and the http request used to exploit a buffer overflow bug in a web service. Variables corresponding to these exploit inputs are usually easy to identify. In our case, however, given the complex information flow from the skeleton app to Android Framework, it is difficult to identify which variables in the execution context have been derived from the skeleton app (Section IV-A). We describe some straightforward thoughts on solving the problem (Section IV-B), and then present an automated and precise solution (Section IV-C).

A. Scattered Symbolic Inputs

Android Framework provides a running environment for all apps, each of which has information stored in Android Framework, such as granted permissions, activities, and intents. There are also variables allocated for system services. The variables used to store the information of different apps and system services are mixed together in the memory address space, and there is no clear boundary between variables derived from the skeleton app and other variables.

A closer look at the Android Framework design shows that there are two distinct types of variables. The first type, called non-app-specific variables, includes those that are allocated and maintained regardless of specific apps in the system. For example, the aforementioned LocationManagerService.mProviders ArrayList is maintained regardless of specific apps. As another example, AudioService.mConnectedDevices is a HashMap that stores currently connected devices and does not depend on specific apps either. There are many other variables belonging to this type; for instance, a set of field variables (mState, mNetworkType, mTypeName, etc.) in the NetworkInfo class that describe the statuses of a network interface. Non-app-specific variables should be used as concrete inputs rather than symbolic ones, as a malicious app typically does not have the capability of manipulating such system data.

The second type, called app-specific variables, stores app-specific information. Some variables store information for all the installed apps; for instance, Settings.mUserIds is an ArrayList that stores the installation data of each installed app (the code path, signature, first install time, last update time, granted permissions, etc.). Others store the information of running apps, such as task affinities, intents, and back stacks.

Unlike the Linux kernel, which stores most information of a process in a centralized structure task_struct, it is notable that the app-specific information is organized according to the system services (rather than apps) probably because Android Framework is programmed as a set of system service classes. Given an app, its related information scatters in many different collection data structures in Android Framework.

The task of selecting symbolic inputs is to find the app-specific variables and to locate elements derived from the skeleton app within the variables. E.g., in addition to determining Settings.mUserIds is an app-specific variable, we need to locate which element in the array is derived from the skeleton app, like looking for a needle in a large pile of hay.

B. Thoughts on Tainting

Tainting is a natural approach that may be used to track the information flow from the skeleton app. By specifying all the return values of function calls that read the apk file of the skeleton app as the taint source, all the tainted variables in the execution context must have been derived from the skeleton app. However, such information flow involves multiple intricate steps, including app installation, system boot, and starting the app. Specifically, after an app is installed, its code and data are stored into multiple files in the system, which are parsed and read at different stages during booting the system and starting the app.

Given the complexity of these steps, it is very unlikely to precisely tracking the information flow throughout these complex steps. First, without taint sanitization, more and more values would become tainted, which results in overtainting [37]. How to insert sanitization properly has been a challenging problem, especially considering the codebase and complex logic of the Android system. In addition, undertainting can arise, for example, when information flow occurs through control dependencies, tainting based on data flow only is inadequate and needs dedicated handling. Therefore, a comprehensive and precise tracking of the information from the skeleton app is hard to achieve.

C. Slim Tainting for Identifying Symbolic Inputs

1) Locating the Needles: Our investigation of Android Framework reveals that app-specific variables are stored in two categories of data structures: array-based ones (built-in arrays, ArrayList, SparseArray, etc.) and hash-table-based ones (HashMap, HashSet, etc.). Given an app, the app’s corresponding element from an app-specific data structure is retrieved in one of the two characteristic ways.

First, given an array-based variable, the Android Framework program retrieves an app’s information in the array using an index that is a function of the app’s UID (an app’s UID is assigned upon installation and not changed). Our investigation shows that there are only two such formulas used to calculate the index. One is \((uid%100,000−10,000)\), converting the user app’s UID into an index to retrieve the element for the app from a built-in array or ArrayList; the other one is \((uid%100,000)\), which is used to calculate the index into a SparseArray. For example, as shown in Figure 2, the first formula is utilized to calculate the index into the ArrayList Settings.mUserIds, which stores the information of all the installed apps with one element for each app.

Second, for hash-table-based variables, the package name (or the package name concatenated with a component name) is used as the key to access elements. Figure 3 shows such an example. Since the skeleton app has a unique UID and package name, they are used as taint sources to track the access to variables derived from the skeleton app.

Given the execution context provided by the concrete execution, we seek to identify variables derived from the
skeleton app, and specify them as symbolic inputs. To achieve it, *slim tainting* is proposed to recognize the characteristic access patterns discussed above, and the tainting is weaved into symbolic execution to specify the identified variables as symbolic inputs just in time. Specifically, the return value of getCallingUID and the package name of the skeleton app are set as taint sources. The taints propagate through (1) the modular and subtraction operations on the UID, and (2) the string assignment and concatenation operations involving the package name. The taint sinks include the get functions of the collection data structures as well as bytecode instructions for loading elements from built-in arrays, such as aaload and iaload, which check whether the index or key being used has been tainted; if so, the corresponding element is set as a symbolic input.

Figure 4 shows two examples. Figure 4a depicts an ArrayList variable mUserIds. The names within the parentheses are the types of the corresponding variables. Assume the skeleton app UID is 10,054. Due to dynamic taint propagation, the calculated index 54 (\(= (uid\%100,000 -10,0000)\)) is tainted; hence, the corresponding element in mUserIds is set as a symbolic input when it is loaded using aaload. Figure 4b shows a HashMap variable mPackages, which uses package names as keys. Since the package name of the malicious app is a taint source, when it is used to retrieve an element from mPackages, the element is identified as a symbolic input when it is retrieved using the HashMap’s get function.

Slim tainting involves very specific taint sources and operations, avoiding the overtainting and undertainting problems in conventional tainting, and requires no manual effort.

2) Relations between Symbolic Inputs: Android Framework contains a large number of complex, pointer-rich data structures. Figure 4 shows such examples. Each element in the ArrayList (Figure 4a) is a reference to a PackageSetting instance, which comprises many references to other complex variables, e.g., a PackageParser.Package class instance; it is notable that symbolic inputs in both the ArrayList (Figure 4a) and the HashMap (Figure 4b) point to the same PackageParser.Package instance directly or indirectly. Such relations are hard coded in Android Framework, and it is critical to take the relations into account during symbolic execution. For example, if the two symbolic input references in Figure 4 were regarded as independent, then each would be considered to be pointing to a separate PackageParser.Package instance; constraints in the path condition that should have described the single PackageParser.Package instance would be split to describe two instances, which is incorrect.

Existing symbolic execution techniques have not resolved the problem of describing the relations between symbolic inputs automatically. Lazy initialization can be used to synthesize a data structure, but still relies on manual effort to write specification about the data structure [28].

To resolve the problem, the concept of *semi-symbolic reference* is proposed for handling reference-based symbolic inputs. Specifically, let \(r\) be a reference that is identified as a symbolic input through tainting, and \(o\) be the object pointed
to be by \( r \). When \( r \) is used to access \( o \), the symbolic executor first examines whether \( o.\text{symbolicHandled} \) is true, where \( \text{symbolicHandled} \) is a flag added to each object indicating whether the host object has been identified as a symbolic input. If it is false, all the primitive-typed fields in \( o \) are set to conventional symbolic inputs, while other reference-typed fields are set to semi-symbolic references (for recursive handling), and \( \text{symbolicHandled} \) is set to true; otherwise, no handling is performed to avoid duplicate processing.

There are several critical points in the solution. First, the solution benefits from the execution context information: when two references point to the same object, they have the same reference value; thus, when an object is processed multiple times due to multiple references pointing to it, the solution can recognize that they point to the same object and ensure the object is identified as a symbolic input only once (based on the \( \text{symbolicHandled} \) flag). For example, in Figure 4, after the \texttt{PackageParser.Package} object is handled once, its \( \text{symbolicHandled} \) flag must be true. Second, a semi-symbolic reference propagates this attribute to all the reference-typed fields in the object it points to, such that they are handled recursively. The propagation is valid as in Android Framework each element in an app-specific data structure is a "cell" that stores information for a specific app; this design ensures that once the execution obtains the reference to some element in an app-specific data structure, the subsequent access is bound to the information of the app stored in that element without worries that the access may reach another app’s information.

V. DECOUPLED ARCHITECTURE

By combining concrete execution and symbolic execution, the state space explosion due to the complex initialization is avoided, but the hybrid execution idea requires a more careful design. This section first describes the design choices we made, and then presents our design.

A. Design Choices

A straightforward design is to augment the Android system to add the capability of symbolic execution by modifying Android Runtime (ART). It takes advantage of the ART’s capability of concrete execution, but requires a lot of modifications to enable symbolic execution, which is very different from concrete execution in terms of thread management, garbage collection, object representation, instruction execution, etc. Therefore, it is challenging to make the two types of execution coexist in the same system. Not only does the compatibility with concrete execution have to be handled carefully, but it implies endless effort to maintain the implementation for the frequently updated Android system.

Instead of implementing a coupled system, we propose to allocate the two kinds of executions to two systems: an original Android system for concrete execution and the other system outside Android for symbolic execution. As the latter is specialized for symbolic execution, its design and implementation are largely simplified. Moreover, since the symbolic execution engine is decoupled from the Android system, it does not need to be maintained when the Android system is updated.

Algorithm 1 Migration of heap information.

```java
function GETFIELD(index)
if objRef = peekStackTop()
fdInfo = getFldInfo(index) ⊲ Class-specific info.
fd = getFd(objRef, fdInfo) ⊲ objRef-specific info.
if !(fd.getSnapshotRefAttribute()) then
return super.getfield(index)
end if
concRef = fd.getValue()
if symRef == NULL then
fdType = fdInfo.getFdType()
if fdType == strRef then
str = snapshot.getStr(concRef)
symRef = newString(str);
symRef = newArray(entryType, len)
snapshot.copyEntries(symRef, concRef)
else ⊲ Other reference types
symRef = newObj(fdType)
snapshot.copyFields(symRef, concRef)
end if
symRef = searchConstantPool(str);
entryType = fdInfo.getEntryType()
len = snapshot.getArrayLen(concRef)
symRef = newArray(entryType, len)
snapshot.copyEntries(symRef, concRef)
else ⊲ strRef
symRef = symRef.getSnapshotRefAttribute()
end if
snapshot.copyStaticFields(objRef)
return super.getfield(index)
end function

TABLE I. BYTCODE INSTRUCTIONS (AND FUNCTION) USED FOR MIGRATING HEAP INFORMATION.

| Instruction | Stack [before] \rightarrow \rightarrow [after] | Description |
|-------------|-----------------------------------|-------------|
| getfield    | objRef \rightarrow value          | get a field value of an object |
| getstatic   | \rightarrow value                 | get a static field value of a class |
| aaload      | arrayRef, index \rightarrow value | load onto the stack a reference from an array |
| initClass   | N/A                               | invoked for class initialization |

B. Migration Algorithm

Symbolic execution is launched by executing a driver program that invokes an entrypoint system interface method. Upon starting, the program counter, register file, and stack all obtain their fresh content, while the heap, which is a collection of classes and objects, needs to be migrated from the execution context provided by the concrete execution.

The heap memory image in the execution context provided by the concrete execution is called a snapshot. We present an algorithm that migrates classes and objects from the snapshot to the JVM for symbolic execution. Whenever a class or object
is referenced, it is migrated from the snapshot by allocating space in the symbolic executor and then copying the fields. The algorithm is built into the symbolic execution engine, which interprets the Java bytecode (of Android Framework) in a non-standard way. Algorithm 1 shows the main migration procedures, which override the interpretation of several bytecode instructions. Table I shows the list of bytecode instructions whose interpretation is overridden to support migration; for each instruction, the effect that the instruction has on the operand stack and the description are included. We first introduce a data structure and a flag that are important for migration, and then describe how objects and classes are migrated.

Migration hash table. A hash table, conc2Sym, is maintained to map reference values in the concrete execution world (where the snapshot has been captured) to ones in the symbolic execution world. Every time an object \( o \) is migrated, a new pair \( \langle r_c, r_s \rangle \) is added to the hash table, where \( r_c \) is the reference value of \( o \) in the concrete execution world and \( r_s \) symbolic. The hash table is maintained for two purposes. First, it prevents duplicate migration of an object; that is, an object pointed to by \( r_c \) is migrated only if \( r_c \) is not found in the hash table. Second, the hash table is used to translate reference values in the concrete execution world, if they exist in the hash table, to ones in the symbolic execution world. The hash table is handled as part of the process state, and gets stored and restored as the path exploration advances and backtracks, respectively.

Reference flag. A flag snapshotRef is associated with each reference-typed field (and each reference-typed element in an array, as well) by the symbolic executor to indicate whether its value is a reference value in the concrete execution world. When an object is newly migrated, the snapshotRef flags of all its reference-typed fields (and elements in an array object) are set to true, since the field values only make sense in the concrete execution world. Once a field is updated with a reference value in the symbolic execution world, its snapshotRef is set to false.

Migrating objects. Given a reference to an object on the stack (Line 2), the instruction getfield pushes a field value of the object onto the stack. If the field’s snapshotRef attribute is false (Line 5; note that, for all primitive-typed fields, getSnapshotRefAttribute returns false), which means that either it is a primitive-typed field or it has a reference value in the symbolic execution world, the instruction’s interpretation is not changed. If snapshotRef is true and the field value concRef is not found in conc2Sym (Line 10), the object should be migrated (Lines 11–26); after migration, the pair \( \langle \text{concRef}, \text{symRef} \rangle \) is added to conc2Sym (Line 27).

How to migrate an object is determined by the object type (Line 11). (1) If the object is a string, the algorithm first searches for a string that has the same value within the runtime constant pool (which stores a set of string literals) in the VM for symbolic execution. If not found, a new string with the same value is created in the symbolic world (Lines 12–17). (2) If the object is an array, an array is allocated and all the elements are copied to the new array (Lines 18–22). This algorithm performs a shallow copy. Thus, for a multi-dimensional array, e.g., \( A[5][10] \), only the 5 elements in the top-level array are copied at this moment. Later, to access any of the 5 elements, the instruction aaload is executed, which is the reason the interpretation of aaload is also overridden to migrate second-level arrays (not shown in Algorithm 1). This reflects the principle of lazy migration: an array object is not copied until a reference to the object is accessed. (3) A reference to an ordinary object is handled by allocating a new object and copying all its fields (Lines 23–25).

While non-static fields are accessed through getfield, access to static fields is through getstatic. Thus, to migrate objects pointed to by static fields, the interpretation of getstatic has to be overridden, and the interpretation is similar to that of getfield.

Migrating classes. When an operation (e.g., an object of a class is created or a class’s static fields are accessed for the first time) triggers initialization of a class during symbolic execution, initClass is invoked by the underlying VM for symbolic execution automatically. For classes that have been initialized during concrete execution, the symbolic executor has to make sure that they are migrated instead of being initialized, considering that the static fields have obtained their values during concrete execution. Thus, when initClass is invoked, the symbolic executor first checks whether the class has been initialized in the concrete execution world; if so, the enclosed static fields in the class are copied from the snapshot to the symbolic execution world (Line 36). In particular, when an object of some class is created in the symbolic world for the first time due to migration (Line 24), it triggers the invocation of initClass first, which migrates the class.

C. Bootstrapping

An important invariant kept during migration is that, whenever a field of an object \( o \) (resp. an element of an array \( A \)) is accessed, \( o \) (resp. \( A \)) must have existed in the symbolic execution world. The invariant is achieved because, upon accessing a reference-typed field, the object pointed to by the field gets migrated. Assume \( f \) is the field whose access triggers the migration of the first object; a natural question is where \( f \) resides. This question is resolved in the test driver.

A test driver simply invokes the entrypoint system interface method and specifies the bootstrap field, whose type is a reference to the system service class that contains the entrypoint method. Figure 5 shows an example of a test driver. A custom annotation fromSnapshot is used to specify the bootstrap field, which is recognized and handled by handleBootstrapField (Line 39 in Algorithm 1), when the TestDriver class is initialized; specifically, handleBootstrapField sets the bootstrap field value to the reference value of the system service object in the concrete execution world, and sets the field’s snapshotRef
attribute to true. (Note that all the system service classes adopt the singleton design pattern, so there is no ambiguity when specifying the reference value.) In Figure 5, for example, when TestDriver is initialized, handleBootstrapField sets the bootstrap field to the reference to the Location Manager service object in the snapshot. Next, when the bootstrap field is accessed, the service object is migrated.

D. Migration Tree

The migration of classes and objects forms a migration tree, which grows as new classes and objects are migrated, rooted at the class and object corresponding to the bootstrap field type. We use the test driver in Figure 5 as an example to illustrate how the migration tree is built, as shown in Figure 6, where the root node is the class and object for LocationManagerService. The migration of a class also triggers the migration of all its super classes, which is not shown in Figure 6 for simplicity.

Part of the resulted migration tree is showed in Figure 7. It also shows the identified symbolic inputs and how the symbolic input attribute propagates. After the element with index 54 in the mUserIds attribute is identified as a symbolic input through tainting, the symbolic input attribute is propagated to other variables pointed to by the element.

VI. IMPLEMENTATION DETAILS

We built the symbolic executor on Symbolic PathFinder (SPF) [33], a symbolic execution framework on top of the Java PathFinder (JPF) [41]. It runs outside the Android system, and does not rely on the Android internals, achieving the goal of a decoupled architecture. This section covers important implementation details for building and configuring the system.

A. Configuration

In addition to specifying the entrypoint system interface and the test driver, we need to provide the Android Framework code and the heap memory snapshot for symbolic execution.

1) Classpath: The Java source code in Android is compiled into .jar files, which comprise standard .class files, and the symbolic executor is built to analyze Java bytecode in such .class files. The classpath below shows the classes analyzed by the symbolic executor.

```
classpath=test_driver_dir;\n  services_intermediates/classes-full-debug.jar;\n  framework_intermediates/classes-full-debug.jar;\n  core-libart_intermediates/classes-full-debug.jar
```

The first line specifies the directory containing the test driver, the next two lines the Android Framework code, and the last line the core libraries of ART, such as utility, io, and math libraries. Several classes (e.g., java.lang.class, .Thread, .StackTraceElement) are modeled by the symbolic executor, but core-libart contains the Android version of these classes; they are hence excluded from core-libart to avoid system initialization failures.

2) Heap Memory Snapshot: After a heap memory snapshot of the System Server process is captured (using the dumpheap utility), it is first converted to a standard .hprof file using the hprof-conv utility included in the Android SDK. The standard .hprof file format opens up the possibility of parsing the snapshot using many existing tools and utilities. In our case, a HPROF heap dump parser is used to extract the list of classes and objects stored in the .hprof file [26]. Based on the parser, we have built an execution context query server that returns classes and objects requested by the symbolic executor.

B. Handling Special calls

1) Handling Service Calls: Service calls are frequently used among services. While inter-process service calls are made through the intricate Binder IPC mechanism, intra-process calls are actually ordinary method calls. Figure 8 shows an example, where the Location Manager service invokes getProfiles exposed by the User Manager service; both services belong to the System Server process. The call at Line 4 leads to a service call at Line 11, which is a virtual function call, whose dispatch relies on the runtime type of the object pointed to by UserManager.mservice. Previous research relies on expert knowledge and specifies the dispatch targets manually to facilitate further analysis [39], [12], [5], while CENTAUR makes use of the runtime type information provided by the execution context, and thus the call is handled as an ordinary virtual function call without requiring expert knowledge or manual effort. This is a concrete example illustrating the advantage of combining concrete and symbolic executions.

2) Dealing with Handler and State Machine Calls: Two other important IPC mechanisms that are widely used by system services are Message Handler and State Machine calls. A handler sends and processes messages associated with a thread’s message queue [25]. When a new handler is created, it is bound to the message queue of the thread that creates it. From that point on, it will deliver messages to that message queue and execute them as they come out of the message queue. To deal with Message Handler calls, when sendMessage(message) is invoked, the invocation is replaced by that of the corresponding Handler’s handleMessage(message). The symbolic executor interposes the invokevirtual instruction and enforces the replacement on the fly.

A State Machine can also send and process messages, which has states arranged hierarchically. A state is an instance of the State class, which implements processMessage
for handling messages. A State Machine sends a message by invoking sendMessage. When a State Machine receives a message, the current state’s processMessage is invoked. Therefore, a key step is to identify the current state. To do it, the field mStateMachine in the State Machine object, which is a reference to the state machine handler, is retrieved (note that when the State Machine object is migrated, all its fields are copied), and then used to migrate the state machine handler object. Next, two fields in the handler object, mStateStack and mStateStackTopIndex, are used to identify the current state (= mStateStack[mStateStackTopIndex].state).

To handle messages sent by a State Machine in the symbolic executor, the invocation of mStateMachine.sendMessage(message) is replaced by that of the current state’s processMessage(message). This way, we connect the senders and receivers for messages sent through State Machine.

3) Handling Calls to Native Code: Part of Android Framework is implemented in native code, which is invoked through the Java Native Interface (JNI) mechanism. Different ways are adopted to handle JNI calls during symbolic execution. First, methods that return the calling UID (getCallingUid()) and the package name of the client app (getPackageName()) are modeled to return the corresponding information for the skeleton app constantly, and the return values are set to be taint sources as aforementioned. Second, the return values of other native methods that return app-specific information of the skeleton app are specified as symbolic inputs. For example, many native methods declared in the package android.content.res access application resources. Third, for native methods that do not have return values they are ignored; ignoring calls to external code has been used in many symbolic execution techniques [10], [33].

Finally, other calls to native methods are delegated back to Android as remote procedure calls. The RPC client in the symbolic executor is built by extending jpf-nhandler [38].
jpfnhandler delegates native calls to a host JVM, this client delegates them to an app running as the RPC server in a remote Android system (Figure 1), which issues delegated native calls using reflection on demand. The Gson library [24] is used for marshalling (and unmarshalling) method parameters and return values, which are transmitted between the RPC server and the client via socket. Note that though an Android system is used to execute native calls, the symbolic executor is decoupled from it using the RPC mechanism.

C. Other Aspects of Symbolic Execution

1) Attributes for Symbolic Execution: JPF supports attributes to be associated with program values including locals, stack operands, and class/object fields in the heap. The framework makes use of attributes to store taints, reference flags, symbolic input attributes, and symbolic expressions.

2) Overriding Bytecode Interpretation: JPF allows replacing or extending the interpretation of bytecode instructions. Interpretation classes for instructions, such as getfield, getstatic, and aaload, are overridden to specify symbolic inputs and migrate the execution context information.

3) Intercepting Method Calls: JPF provides a mechanism called Model Java Interface (MJI) that intercepts method invocations for custom handling. CENTAUR makes use of MJI to intercept certain method calls (e.g., getCallingUid, getPackageName, and the get functions of various collection data structures), and redirects them to our custom implementation of these functions. This mechanism is also used by the RPC client for intercepting calls to native code.

VII. Evaluation

A. Experiment Settings and Overview

The experiments were performed on a machine with an Intel Core i7 4.0Ghz Quad Core processor and 32GB RAM running Linux kernel 3.13. Exploits were generated on Android Framework 5.0, and verified using different versions of Android systems and settings.

We first present two case studies that demonstrate the applications of CENTAUR. They show two typical scenarios of applying CENTAUR. The first case study illustrates how static analysis and symbolic execution are combined to find vulnerabilities and generate exploits. The second case study relies on the CENTAUR system only.

Next, the reliability of the approach based on heap memory snapshots is investigated. We present exploit generation experiments based on snapshots captured at different times, and analyze the results.

Finally, we compare symbolic execution used in CENTAUR against under-constrained symbolic execution (UCSE). Both can start symbolic execution from system interface methods instead of the main function to reach the code deep in the program, but CENTAUR makes use of the execution context provided by concrete execution to improve the precision and efficiency of symbolic execution.

B. Case Study 1: Exploiting Inconsistent Security Policy Enforcement (ISPE)

1) Background: Android Framework utilizes a permission-based security model, which provides controlled access to various system resources. However, a sensitive operation may be reached from different paths, which may enforce security checks inconsistently. As a result, an attacker with insufficient privilege may perform sensitive operations by taking paths that lack security checks. Recently, static analysis combined with manual code inspection has been applied to finding such inconsistent security enforcement cases in Android Framework [39]. The system, called Kratos, first builds a call graph based on the Android Framework code. With the call graph, it finds all the execution paths that can reach sensitive operations. Kratos then compares the paths pairwise to identify paths that reach the same sensitive operation with inconsistent security checks enforced, and reports them as suspected ISPE vulnerabilities, as they violate the security property that all paths should have consistent permissions for reaching a given sensitive operation.

2) Combined Approach for Bug Finding: While static analysis is very scalable, it is well known that the analysis results may be imprecise. In the case of finding ISPE bugs, static analysis based on the reachability analysis may report false positives, as some paths may be infeasible in real executions. Currently, manual effort is used to scrutinize the code along each reported path, which is laborious and tedious; moreover, it is difficult to verify the correctness of the manual inspection.

We propose to combine static analysis and symbolic execution to find ISPE bugs. For each suspected vulnerability reported by static analysis, CENTAUR (1) finds all feasible paths that reach the sensitive operation, (2) gives permissions needed for each feasible path (the needed permissions are included in each path condition), (3) verifies permission consistency among the feasible paths, and (4) generates inputs that exercise the feasible paths to verify suspected vulnerabilities. It thus demonstrates the applications of CENTAUR comprehensively. All the steps have been performed automatically, in contrast with previous work that relies on tedious and error-prone manual inspection. In addition, zero false positives are guaranteed as all suspected vulnerabilities are validated by the generated inputs.

Table II summarizes the experiment results (the vulnerability shown in the last row is discussed in Case Study 2). For each vulnerability, the table lists the vulnerability description, entrypoint(s), the min/max number of migrated classes among different paths, the min/max number of migrated objects among different paths, the number of sets of concrete values generated (“-“ means it can be exploited unconditionally), the number of sets that can be used to generate exploits, the symbolic execution time, whether the suspected vulnerability is really exploitable, and whether the results are consistent with those of Kratos.

Given an entrypoint method, there may be multiple paths that reach the sensitive operation, and the classes and objects involved in the paths may vary, as illustrated by the min/max number of migrated classes and objects. Note that when migrating a class, all its super classes are also migrated, which is the reason the number of migrated classes is greater than that of objects. In the majority of the cases, the symbolic execution of an entrypoint method is finished within less one
minute. All the cases are verified using the inputs generated by CENTAUR, showing they are exploitable.

New findings. It is notable that some of our results are inconsistent with those of Kratos. First, for the fifth vulnerability in Table II, Kratos reports that it does not exist in Android Framework 5.0, while CENTAUR shows that it still exist (i.e., different permissions are required by the two system interface methods for reaching the sensitive resource) and the result is verified using inputs generated by CENTAUR. Second, for the sixth vulnerability in Table II, Kratos reports only one permission CONNECTIVITY_INTERNAL for invoking NsdService.setEnabled, while CENTAUR reports two permissions, CONNECTIVITY_INTERNAL and WRITE_SETTINGS. The more thorough and accurate results demonstrate the advantages of the hybrid approach.

3) A Detailed Example: As an example, we describe in detail how the combined approach was applied to finding the first vulnerability in Table II. First, the static analysis based on path reachability and pairwise path comparison finds that both getProviders(Criteria, boolean) and getAllProviders() (in the LocationManagerService class) have paths reaching the same sensitive operation that returns the names of the installed GPS providers, and the two paths can be executed with inconsistent permissions; thus, it is a suspected vulnerability. Next, CENTAUR is applied to validating it automatically. Specifically, after the Android system is initialized and the skeleton app is launched, a heap memory snapshot of the process, so are handled as ordinary method calls using the runtime type information in the execution context.

Four native methods are involved: getCallingUid, getCallingPid, getuid, and native_get_long. Calls to these methods are intercepted using MJI, and are redirected to our handlers of these methods. The first two return the UID and PID of the client app, respectively, and getuid returns the UID = 1000, which is the UID of the System Server process. The call to native_get_long is delegated back to the Android system through RPC.

Fig. 9. Sub-call graph rooted at getProviders(Criteria, boolean). (LMS, AMS, and PMS represent LocationManagerService, ActivityManager, ActivityManagerService, and PackageManagerService, respectively. The grey nodes denote native methods.)

The variable mUserIds.array[54] is identified as a symbolic input through the tainting during symbolic execution. Figure 10 shows several examples of the generated concrete values. Take the first set as an example; it provides clear information for building an app that exercises the ACCESS_FINE_LOCATION permission and preparing the

### Table II. List of Vulnerabilities.

| No. | Vulnerability description | Entrypoint(s) | # of migrated classes | # of migrated objects | # of all sets | # of legal sets | Sym. exe. time | Exploitable? | Consistent with Kratos? |
|-----|--------------------------|---------------|-----------------------|-----------------------|---------------|----------------|----------------|-------------|------------------------|
| 1   | Access installed providers with insuf. privilege | LMS.getAllProviders() | 55 55 | 4 4 | — — | 14s | ✓ | ✓ |
| 2   | Read phone state with insuf. privilege | TS.nextState() | 48 48 | 3 3 | — — | 23s | ✓ | ✓ |
| 3   | End phone calls with insuf. privilege | TS.endCall() | 81 81 | 21 24 | 1 1 | 18s | ✓ | ✓ |
| 4   | Close system dialogs with insuf. privilege | WMS.closeSystemDialogs() | 57 57 | 6 6 | — — | 11s | ✓ | ✓ |
| 5   | Set up HTTP proxy working in PAC mode with insuf. privilege | WSI.addOrUpdateNetwork() | 67 67 | 23 52 | 18 18 | 1m 06s | ✓ | ✓ |
| 6   | Enable/Disable mDNS daemon with insuf. privilege | NS.setEnabled() | 11 11 | 28 53 | 1 1 | 37s | ✓ | ✓ |
| 7   | Task hijacking | ASS.startActivityUncheckedLocked() | 324 387 | 136 182 | 2,020 | 810 | 14m 33s | ✓ | N/A |
C. Case Study 2: Constructing Task Hijacking Attacks

1) Background: The Activity Manager Service (AMS) allows activities of different apps to reside in the same task, which is a collection of activities that users interact with when performing a certain job. The activities in a given task are arranged in a back stack, pushed in the order they were opened; users can navigate back using the “Back” button. This feature can be exploited by a malicious app if its activities are manipulated to reside side by side with the victim apps in the same task and hijack the user sessions of the victim app. This is a design flaw rather than a program bug, and can be exploited to implement UI spoofing, denial-of-service, and user monitoring attacks [36]. For example, a malicious app may start a malicious activity that impersonates the victim activity, and the UI spoofing attack succeeds if the fake activity resides in the same back stack as the target victim activity, and the user may mistake the fake malicious activity for the victim one.

As the needed permissions required by the two entrypoints differ, it is identified as an ISPE vulnerability. We then checked the reliability of the exploits. 60 emulators with different device types, Android framework versions (4.3, 4.4, and 5.0), and CPU/ABI configurations were used to check whether the completed apps could access the targeted sensitive resource. The experiments show that the apps are effective on all the emulators, as the different configurations among the emulators do not affect the invocation and execution of the system interface methods. It demonstrates the reliability of the exploits.

Summary. Compared to previous work that relies on enormous and error-prone manual inspection, the combined approach of static analysis and symbolic execution eliminates the need for manual work and guarantees zero false positives. It is potential to apply this approach to finding other types of vulnerabilities in Android Framework.

The security property here is that the malicious activity should not reside in the same back stack as the target victim activity.

This case illustrates unique characteristics of generating exploits that take advantage of Android Framework vulnerabilities: while the design flaw is due to Android Framework, the victim entity is not the framework but another app, and the malicious “input” is not a simple string input but a separate app. It is very different from exploit generation targeting a vulnerable executable, which typically involves a single entity (the vulnerable executable) and the attack input is usually in the form of a string.

2) Bug Finding: We use the EditEventActivity activity of the com.android.calendar app as an example victim activity. In the skeleton app, the main activity of the skeleton app starts the malicious activity, denoted by $M$. The goal of the attack is that $M$, when it is started, will reside in the same task as the victim activity. A bug is identified if such attacks against the victim activity is feasible. We capture the heap memory snapshot when the victim app and the skeleton app are started and the main activity of the skeleton app is ready to start the malicious activity.

Figure 11 shows the rough procedure of starting the malicious activity. The API `Activity.startActivity(Intent, Bundle)` is invoked with the parameters specifying the activity to be started, i.e., $M$. The invocation leads to a service request to be handled by the service interface method `startActivity` in AMS. The operations of selecting the task hosting the new activity are performed in `startActivityUncheckedLocked`, which has eight parameters as shown in Figure 12. The first parameter $r$ is an `ActivityRecord` instance storing the information of $M$, while the second storing that of the caller activity. The description of other parameters is omitted. They are set to symbolic inputs.

The constraint indicating that the task selected for $M$ is
Fig. 13. Examples of concrete input values generated in case study 2.

```java
// Illegal concrete values
(r.intent.mFlags == 0x10000000) &&
(r.launchMode == LAUNCH_SINGLE_TOP) &&
(r.mLaunchTaskBehind == true) &&
(options == null) &&
(r.info.documentLaunchMode == 0) &&
(r.info.targetActivity == null) &&
(r.resultTo == null) &&
(r.taskAffinity != "android.task.calendar") &&
(r.intent.mComponent.mClass == "com.android.calendar.EditEventActivity") &&
(r.intent.mComponent.mPackage == "com.android.calendar")

// Legal concrete values
(r.intent.mFlags == 0x10000000) &&
(r.launchMode == LAUNCH_SINGLE_TASK) &&
(r.mLaunchTaskBehind == true) &&
(options == null) &&
(r.resultTo == null) &&
(r.info.documentLaunchMode == 0) &&
(r.info.targetActivity == null) &&
(r.taskAffinity == "android.task.calendar")
```

| Android version | 4.0 | 4.1 | 4.2 | 4.3 | 4.4 | 5.0 |
|-----------------|-----|-----|-----|-----|-----|-----|
| # of effective exploits | 434 | 674 | 674 | 674 | 702 | 810 |

**TABLE III. Effectiveness of the generated exploits.**

Fig. 14. Exploit generated from the concrete input values.

```java
public void onCreate(Bundle savedInstanceState) {
    ...
    Intent i = new Intent(this, maliciousActivity.class);
    intent.setFlags(0x10080000);
    startActivity(i, null);
}
```

Fig. 15. Exploiting condition.

```java
(((r.intent.mFlags & 0x7F7FFFFF) | 0x10000000) & 0x80000) != 0x80000
```

Exactly the one hosting the victim activity is added to each of the path conditions when it is to be resolved. A feasible path is found if the path condition is resolvable.

3) Exploit Generation: The symbolic execution generated 2,020 sets of concrete input values, among which some contain illegal concrete values, e.g., due to requiring the malicious activity's package and activity names to be equal to those of the victim activity. Simple scripts were written to filter out illegal concrete values, the number of which is 1,210 sets totally. Figure 13 (upper part) shows an example of illegal concrete values; it is illegal because its package name is duplicate with that of the victim app, but Android requires that each app should have a unique package name.

Figure 13 (lower part) shows an example of the rest 810 sets of legal concrete values. In this example, r.intent.mFlags and options guide how to set the input parameters of startActivity for starting the malicious activity; others instruct how to configure the malicious activity; for example, r.launchMode is mapped to the android:launchMode in the manifest file. Figure 14 shows the exploit according to the set of concrete values. When users click the app icon of the malicious app in the home screen, the main activity will be started and it is coded to call startActivity to start the malicious activity, which will reside side by side with the victim activity in the same task.

We then examined whether the exploits generated on Android 5.0 were effective on other versions of Android systems. Table III lists the results, which show that the effectiveness of the exploits are affected by the versions of Android systems. Further investigation has revealed that the difference is mainly caused by code changes. For example, the new exploiting condition FLAG_ACTIVITY_NEW_DOCUMENT is not introduced until Android 5.0 (discussed below); the API startActivity(Intent, Bundle) is not included in version 4.0, and thus only exploits with options == null can be used for invoking startActivity(Intent).

**Newly discovered exploiting condition.** The path conditions generated from symbolic execution reveal a new exploiting condition, as shown in Figure 15, that was not reported in previous work [36]. Here, 0x80000 represents the flag FLAG_ACTIVITY_NEW_DOCUMENT, which is introduced since Android 5.0, and the seemingly complex condition simply means the corresponding bit in the bitflags r.intent.mFlags is 0. Compared to previous work that relies on ad hoc manual effort for discovering the exploiting conditions, CENTAUR finds them in a systematic and automatic way.

**D. Consistency of Exploits Generated with Different Snapshots**

We then investigated whether snapshots captured at different times affected exploit generation. After the system is initialized, 20 snapshots were captured at intervals of 5 minutes on Android 5.0 with random user interactions during the intervals. For each vulnerability listed in Table II, symbolic execution was performed with each of the 20 snapshots providing the execution context. The results show that, for each vulnerability, the same sets of path conditions were generated with different snapshots, which means that the resulting exploits with the different snapshots are consistent.

There are several reasons that explain the consistency of exploits. First, if a malicious app does not rely on other apps to exploit a vulnerability (e.g., inconsistent security policy enforcement), access control is enforced in Android Framework to make sure the information of other apps is not accessed. Thus, the configurations and statuses of other apps do not affect the path exploration. On the other hand, for exploits that rely on the statuses of other apps (e.g., the victim app in task hijacking attacks), the path exploration probably depends on the statuses of one or more apps. During symbolic execution, reasonable setting up is established consistently; for example, the victim activity should already be started in the task hijacking case prior to capturing snapshots. The results show that an attack succeeds as long as the same statuses recur.
Finally, the values of non-app-specific variables do not affect path exploration for the vulnerabilities we examined. For example, in the case of inconsistent security policy enforcement for accessing the names of installed providers, the path exploration does not depend on the concrete values of the related non-app-specific variable (i.e., `LocationManagerService.mProviders`), although different provider names may be returned by the service calls if different providers are installed.

### E. Comparison with Under-constrained Symbolic Execution (UCSE)

Both CENTAUR and UCSE are able to start symbolic execution at any service interface method of Android Framework. The major difference between the two is that UCSE does not have the type and value information about the inputs, while CENTAUR obtains the information from the execution context provided by the concrete execution.

The first issue of applying UCSE to symbolic execution of Android Framework is that virtual function calls are frequently used, but the runtime types of the receiver objects are unknown. UCSE constructs the receiver objects either using lazy initialization based on the type hierarchy or relying on manual specifications, which either explores spurious paths or requires much manual effort.

The second issue is that input variables which are treated as concrete inputs in CENTAUR are treated as symbolic inputs in UCSE. UCSE handles such symbolic inputs using lazy initialization, which causes the following problems: (1) loops that iterate through collection data structures are unbounded, and (2) the generated concrete values are unrealistic.

We tried to perform UCSE of Android Framework using Java Pathfinder, which kept crashing when it was applied directly. We spent a lot of time and tedious effort modifying the framework code (e.g., adding the type information about objects pointed to by references to assist dynamic dispatching) to make the symbolic execution possible. We thus only modified the code with respect to the ISPE vulnerability of accessing the GPS provider list and the task hijacking vulnerability. Table IV shows the execution time applying the two techniques. Due to path explosion UCSE in both cases ran out of memory.

Therefore, path exploration without precise information of the execution context causes many problems, such as requiring tedious manual effort, generating unrealistic outputs, and exploring spurious paths. CENTAUR resolves the problems by migrating the execution context from the concrete execution world to symbolic execution.

### VIII. Related Work

#### Mixing Concrete/Symbolic Execution

DART is the first concolic testing tool that uses symbolic analysis in concert with concrete execution to improve coverage of random testing [21]. It runs the tested unit code on random inputs and symbolically gathers constraints at decision points that use input values; then, it negates one of these symbolic constraints to generate the next test case. EGT [9], EXE [10] and KLEE [8] execute external code concretely by using one of the possible concrete values of the symbolic operands. S²E introduces selective symbolic execution, which allows a program’s paths to be explored without having to model its surrounding environment [13]. These techniques usually take advantage of concrete execution to simplify complex symbolic constraints and execute external code, while CENTAUR makes use of concrete execution to set up the execution context for symbolic execution.

#### Switching Concrete Execution to Symbolic Execution

Symbolic Pathfinder (SPF) begins with concrete execution and can switch to symbolic execution at any point in the program [32]. CENTAUR allocates concrete execution and symbolic execution to two decoupled systems, so that the two systems can evolve independently. As SPF aims at generating unit test cases, it simply specifies function parameters as symbolic inputs, while CENTAUR finds out variables derived from the malicious app and uses them as symbolic inputs.

#### Bug Finding

Fuzzing and symbolic execution have been applied to checking the existence of bugs. For example, Miller et al. proposed a blackbox fuzzing technique that sends unstructured random inputs to an application program and considers a failure to be a crash or hang [29]. It is mainly used to reveal input validation bugs [31], [11]. SAGE is a bug finding system [22], which leverages the technique described in DART [21]. SAGE has demonstrated symbolic execution can be very useful for bug finding. Through symbolic execution of Android Framework, CENTAUR shows its effectiveness for bug finding as well.

#### Exploit Generation

Automatic patch-based exploit generation (APEG) generates exploits based on information in patches [7]. Compared to APEG, AEG does not require access to patches. Both APEG and AEG target stand-alone native executables for exploit generation, while CENTAUR considers exploit generation in an environment that manages all executables running on it. Many unique challenges not seen in stand-alone executables have to be addressed by CENTAUR.

#### Symbolic Execution of Android Apps

There has been a lot of work that leverages symbolic execution for testing Android apps. For example, Jensen et al. proposed to use concolic execution to build summaries of the individual event handlers and then generate event sequences backward, in order to find event sequences that reach a given target line of code in the Android app [27]. SIG-Droid combines program analysis techniques with symbolic execution to generate event sequences as well as input values [30]. All use symbolic execution to exercise application code. To our knowledge, our system is the first one that supports symbolic execution of Android Framework.

### IX. Conclusions

We have introduced the first system for automatic generation of exploits that take advantage of Android Framework vulnerabilities. To avoid state space explosion due to the complex initialization, concrete execution is used for the initialization phase, providing execution context to symbolic execution. Among the large number of variables in execution context, slim tainting tracks characteristic access patterns to identify

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**TABLE IV. EXECUTION TIME OF UCSE AND CENTAUR.**

| Vulnerability               | UCSE  | CENTAUR |
|-----------------------------|-------|---------|
| TSPE in accessing GPS providers | Out-of-mem | 1m 42s  |
| Task hijacking              | Out-of-mem | 14m 33s |
variables derived from the malicious apps as symbolic inputs. In order to decouple the implementation of CENTAUR from Android, the execution context provided by concrete execution variables derived from the malicious apps as symbolic inputs. Given that symbolic execution has proven to be a very useful technique, we plan to apply CENTAUR to other purposes in future work, such as automatic API specification generation, fine-grained malware analysis, and testing.

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