

ACMiner: Extraction and Analysis of Authorization Checks in Android’s Middleware

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ABSTRACT

Billions of users rely on the security of the Android platform to protect phones, tablets, and many different types of consumer electronics. While Android’s permission model is well studied, the *enforcement* of the protection policy has received relatively little attention. Much of this enforcement is spread across system services, taking the form of hard-coded checks within their implementations. In this paper, we propose Authorization Check Miner (ACMiner), a framework for evaluating the correctness of Android’s access control enforcement through consistency analysis of authorization checks. ACMiner combines program and text analysis techniques to generate a rich set of authorization checks, mines the corresponding protection policy for each service entry point, and uses association rule mining at a service granularity to identify inconsistencies that may correspond to vulnerabilities. We used ACMiner to study the AOSP version of Android 7.1.1 to identify 28 vulnerabilities relating to missing authorization checks. In doing so, we demonstrate ACMiner’s ability to help domain experts process thousands of authorization checks scattered across millions of lines of code.

1 INTRODUCTION

Android has become the world’s dominant computing platform, powering over 2 billion devices by mid-2017 [11]. Not only is Android the primary computing platform for many end-users, it also has significant use by business enterprises [34] and government agencies [35, 38]. As a result, any security flaw in the Android platform is likely to cause significant and widespread damage, lending immense importance to evaluating the platform’s security.

While Android is built on Linux, it has many differences. A key appeal of the platform is its semantically rich application programming interfaces (APIs) that provide application developers simple and convenient abstractions to access information and resources (e.g., retrieve the GPS location, record audio using the microphone, and take a picture with the camera). This functionality, along with corresponding security checks, is implemented within a collection of privileged userspace services. While most Android security research has focused on third party applications [7, 14, 16, 19, 20, 36, 37, 40], the several efforts that consider platform security

highlight the need for more systematic evaluation of security and access control checks within privileged userspace services (e.g., evidence of system apps re-exposing information without security checks [25, 44], or missing checks in the Package Manager service leading to Pile-Up vulnerabilities [45]).

To date, only two prior works have attempted to evaluate the correctness of access control logic within Android’s system services. Both Kratos [39] and AceDroid [2] approximate correctness through consistency measures, as previously done for evaluating correctness of security hooks in the Linux kernel [13, 30, 42]. However, these prior works have limitations. Kratos only considers a small number of manually-defined authorization checks (e.g., it excludes App Ops checks). AceDroid considers a larger set of authorization checks, but these are still largely manually defined, primarily through observation. Kratos performs coarse-grained analysis using call-graphs, leading to imprecision. AceDroid’s program analysis provides better precision, but oversimplifies its access control representation, making it difficult to identify vulnerabilities within single system images.

In this paper, we propose Authorization Check Miner (ACMiner), a framework for evaluating the correctness of Android’s access control enforcement through consistency analysis of authorization checks. ACMiner is based on several novel insights. First, we avoid identification of protected operations (a key challenge in the space) by considering program logic between service entry points and code that throws a `SecurityException`. Second, we propose a semi-automated method of discovering authorization checks. More specifically, we mine all constants and names of methods and variables that influence conditional logic leading to throwing a `SecurityException`. From this dataset, we identify security-relevant values (e.g., “restricted”) and develop regular expressions to automatically identify those conditions during program analysis that mines policy rules from the code. Third, we use association rule mining to identify inconsistent authorization checks for entry points in the same service. Association rule mining has the added benefit of suggesting changes to make authorization checks more consistent, which is valuable when triaging results. By applying this methodology, ACMiner allows a domain expert (i.e., a developer familiar with the AOSP source code) to quickly identify missing authorization checks that allow abuse by third-party applications.

We evaluated the utility of ACMiner by applying it to the AOSP

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code for Android 7.1.1. Of the 4,004 total entry points to system services, ACMiner identified 1,995 with authorization checks. Of these entry points, the association rule mining identified inconsistencies in 246. We manually investigated these 246 entry points with the aid of the rules suggested by the association rule mining, which allowed us to identify 28 security vulnerabilities. ACMiner not only reduced the effort required to analyze system services (i.e., by narrowing down to only 246 entry points out of 4004), but also allowed us to rapidly triage results by suggesting solutions. Out of the 28 security vulnerabilities, 7 were in security-sensitive entry points that may be exploited from third-party applications, and an additional 12 were in security-sensitive entry points that may be exploited from system applications. The rest were in entry points with relatively low security value. All 28 vulnerabilities have been reported to Google. At the time of writing, Google has confirmed 2 of these vulnerabilities as “moderate severity.”

This paper makes the following contributions:

- We design and implement ACMiner, a framework that enables a domain expert to identify and systematically evaluate inconsistent access control enforcement in Android’s system services. Our results show that this analysis is not only useful for identifying existing vulnerabilities, but also inconsistencies that may lead to vulnerabilities in the future.
- We combine program and text analysis techniques to generate a rich set of authorization checks used in system services. This technique is a significant improvement over prior approaches that use manually-defined authorization checks.
- We use ACMiner to evaluate the AOSP version of Android 7.1.1 and identify 28 vulnerabilities. All vulnerabilities have been reported to Google, which at the time of writing has classified 2 as “moderate severity.”

We designed ACMiner to give security researchers and system developers deep insights into the security of Android’s system services. This paper describes how ACMiner can systematically analyze the consistency of the authorization checks in the system services. However, ACMiner may also be useful for other forms of analysis. For instance, ACMiner can aid regression testing, as it can be extended to highlight changes to the policy implementation on a semantic level. The information extracted by ACMiner can also be used to study the evolution of access control in Android, potentially discovering new vulnerabilities. Finally, since changes by OEMs have historically introduced vulnerabilities, OEMs can use ACMiner to validate their implemented checks against AOSP.

The remainder of this paper proceeds as follows. Section 2 provides background. Section 3 describes the challenges and provides an overview of ACMiner. Section 4 describes the design of ACMiner in detail. Sections 5 and 6 describe our analysis of the system services of AOSP 7.1.1. Section 7 describes the limitations of our approach. Section 8 discusses related work. Section 9 concludes.

2 BACKGROUND AND MOTIVATION

The Android middleware is implemented using the same component abstractions as third-party applications [17]: activities, content providers, broadcast receivers, and services. In this paper, we only consider service components, which provide daemon-like functionality. Apps interface with service components via the Binder

```

1 // Entry point with correct authorization checks
2 boolean hasBaseUserRestriction(String key, int userId) {
3     checkManageUsersPermission("hasBaseUserRestriction");
4     // Unique check without a SecurityException
5     if (!UserRestrictionsUtils.isValidRestriction(key))
6         return false;
7     ...}
8
9 // Entry point missing checkManageUsersPermission
10 boolean hasUserRestriction(String key, int userId) {
11     if (!UserRestrictionsUtils.isValidRestriction(key))
12         return false;
13     ...}
14
15 void checkManageUsersPermission(String message) {
16     if (!hasManageUsersPermission())
17         throw new SecurityException();}
18
19 boolean hasManageUsersPermission() {
20     int callingUid = Binder.getCallingUid();
21     return UserHandle.isSameApp(callingUid,
22         Process.SYSTEM_UID
23         || callingUid == Process.ROOT_UID
24         || ActivityManager.checkComponentPermission(
25             "android.permission.MANAGE_USERS",
26             callingUid, -1, true) ==
27         PackageManager.PERMISSION_GRANTED);}

```

Figure 1: Vulnerability found in UserManagerService by our tool

inter-process communication (IPC) mechanism, which consists of sending *parcel* objects that indicate the target interface method being called via an integer. For the most part, Android’s system services use the Android Interface Description Language (AIDL) to automatically generate the code that unmarshals these parcels. Moreover, when interfacing with system services, third party apps rely on public APIs implementing a *proxy* to construct the parcel. When the parcel is unmarshalled by the service interface, the arguments are passed to a *stub* that calls the corresponding *entry point* method in the service component. While not all service entry points have corresponding public APIs, any third-party application can use reflection to invoke the entry points for “hidden” APIs.

Android uses two broad techniques to enforce access control. For coarse-grained checks (i.e., at the component level), the Activity Manager Service (AMS) enforces policy specified in application manifest files. This paper focuses on fine-grained checks (i.e., at the service entry point level), which are enforced using hard-coded logic within the service implementation. This hard-coded logic includes variants of the `checkPermission` method, Unix Identifier (UID) checks, as well as many subtle checks based on service-specific state. Prior work [2, 39] has primarily relied on manual enumeration of these checks, which is error prone. To simplify discussion in this paper, we refer to such methods that return or check Android system state as *context queries*.

Figure 1 provides a motivating example for this paper, which contains a vulnerability discovered by ACMiner. The simplified code snippet is from the User Manager Service, which provides core functionality similar to the Activity Manager and Package Manager Services. In the figure, there are two entry points: `hasBaseUserRestriction` and `hasUserRestriction`. The entry points perform very similar functionality, but have inconsistent authorization checks. Specifically, `hasBaseUserRestriction` throws a `SecurityException` if the caller does not have the proper UID or permission.

This example is particularly apropos to ACMiner, because `hasUserRestriction` does not call any of the context queries considered

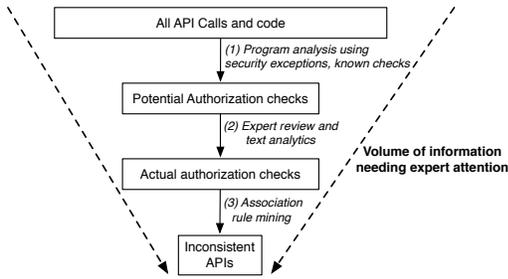


Figure 2: Overview of ACMiner. At each stage, ACMiner significantly reduces the information an expert needs to analyze.

by prior work [2, 39]. It also does not throw a `SecurityException`. Without knowledge that `isValidRestriction` is an authorization check, no form of consistency analysis could have identified that `hasUserRestriction` has a missing check.

3 OVERVIEW

The goal of this paper is to help a domain expert quickly identify and assess the impact of incorrect access control logic in implementations of system services in Android. As with most nontrivial software systems, no ground truth specification of correctness exists. Rather, the “ground truth” resides largely within the heads of the platform developers. Prior literature has approached this type of problem by approximating correctness with consistency. The intuition is that system developers are not malicious and that they are likely to get most of the checks correct. The approach was first applied to security hook placement in the Linux kernel [13, 30, 42] and more recently the Android platform [2, 39].

Evaluating authorization check correctness via consistency analysis requires addressing the following challenges.

- *Protected Operations:* Nontrivial systems rarely have a clear specification of the functional operations that require protection by the access control system. Protected operations range from accessing a device node to reading a value from a private member variable. `Explorer` [6] attempts to enumerate protected operations for Android; however, the specification is far from complete.
- *Authorization Checks:* What constitutes an authorization check is vague and imprecise. While some authorization checks are clear (e.g., those based on `checkPermission` and `getCallingUid`), many others are based on service-specific state and the corresponding authorization checks use a variety of method and variable names.
- *Consistency:* The granularity and type of consistency impacts the precision and utility of the analysis. While increasing the scope of relevant authorization checks increases the noise in the analysis, not considering all authorization checks (as in `Kratos` [39]) or using heuristics to determine relevancy (as in `AceDroid` [2]) raises the risk of not detecting vulnerabilities.

ACMiner addresses these challenges through several novel insights. First, ACMiner avoids the need to specify protected operations by considering program logic between service entry points and code that throws a `SecurityException`. Our intuition is that if one control flow path leads to a `SecurityException`, an alternate control flow path leads to a protected operation. Furthermore, the

conditional logic leading to the `SecurityException` describes the authorization checks. However, we found that not all authorization denials lead to a `SecurityException`, therefore, we also include entry points that contain known authorization checks. Second, ACMiner semi-automatically discovers new authorization checks using a combination of static program analysis and textual processing. More specifically, ACMiner identifies all of the method names, variable names, and strings that influence the conditional logic leading to a `SecurityException`. The security-relevant values are manually refined and used to generate regular expressions that identify a broader set of authorization checks within service implementations. Third and finally, ACMiner uses association rule mining for consistency analysis. For each entry point, ACMiner uses static program analysis to extract a set of authorization checks. Association rule mining compares the authorization check sets between entry points in the same service. The analysis produces suggestions (called “rules”) of how the sets should change to make them more consistent. These rules include confidence scores that greatly aid domain experts when triaging the results. This general approach is depicted in Figure 2.

To more concretely understand how ACMiner operates, consider the discovery of the vulnerability shown in Figure 1. As a pre-processing step, ACMiner helps a domain expert semi-automatically identify authorization checks. First, ACMiner determines that the return value of `isValidRestriction` controls flow from the entry point `hasBaseUserRestriction` to a `SecurityException`. As such, this method name, along with many security irrelevant names are given to a domain expert. The domain expert then identifies security relevant terms (e.g. “restriction”), which ACMiner consumes as part of a regular expression. Next, ACMiner mines the policy of the User Manager Service, extracting a policy for both `hasBaseUserRestriction` and `hasUserRestriction`, with the policy for `hasUserRestriction` only being extracted because `isValidRestriction` was identified as an authorization check. For each entry point, the policy is then encoded as a set of authorization checks (e.g. `isValidRestriction` and `ROOT_UID == getCallingUid()`). Finally, ACMiner performs association rule mining to suggest set changes that make the policy more consistent. Such suggestions led us to discover the vulnerability in `hasUserRestriction`.

4 DESIGN

ACMiner is constructed on top of the Java static analysis framework Soot [31, 43] and has been largely parallelized so as to improve the run time of the complex analysis of Android’s services. The design of ACMiner can be divided into three phases: (§4.1) Mining Authorization Checks, (§4.2) Refining Authorization Checks, and (§4.3) Inconsistency Analysis.

4.1 Mining Authorization Checks

The first phase of ACMiner is mining authorization checks. This phase consist of the following program analysis challenges: (§4.1.1) Call Graph Construction, (§4.1.2) Identifying Authorization-Check Statements, and (§4.1.3) Representing Authorization Checks.

4.1.1 Call Graph Construction. Authorization checks are mined by traversing a call graph of the service implementation. ACMiner constructs call graphs using the following three steps.

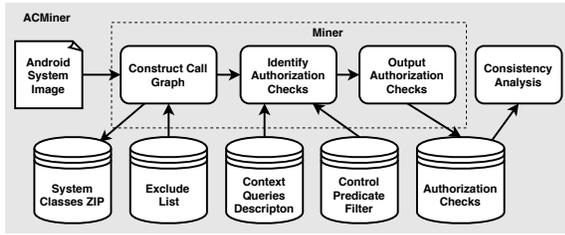


Figure 3: ACMiner’s processing stages and input files.

Extracting Java Class Files: ACMiner extracts a *.jar* containing all the class files of the Android middleware in Soot’s Jimple format from Android’s *system.img*. This *.jar* containing Jimple files is then used on all subsequent runs of ACMiner. The implementation of this approach is detailed in Appendix A.

Extracting System Services and Entry Points: Android’s middleware is composed of isolated services that communicate through predefined Binder boundaries. This division allows ACMiner to analyze each service separately, by defining each service by the code reachable through its Binder entry points. ACMiner extracts system services and their entry points similar to prior work [2, 5, 39]. For implementation details, please see Appendix B.

Reducing the Call Graph: ACMiner constructs a call graph representing all possible transitive calls from the entry points. ACMiner uses the Class Hierarchy Analysis (CHA) [12], which is guaranteed to provide an over-approximation of the actual runtime call graph. In contrast, Kratos and AceDroid use other potentially more accurate call graph builders (i.e., SPARK [33] and its WALA equivalent), which use points-to analysis to construct a less complete under-approximation of the runtime call graph. The loss of completeness occurs when constructing call graphs for libraries and other Java code without main methods. Therefore, it is important to note that unlike the prior work, ACMiner is more complete and guaranteed to include all paths containing authorization checks.

Since CHA call graphs are coarse over-approximations of the runtime call graph, ACMiner must apply heuristics to mitigate call graph bloat. When resolving targets for method invocations, CHA considers every possible implementation of the target method whose declaring type is within the type hierarchy of the call’s receiver type. If the invoked method is defined in a widely used interface or superclass, the resolution may identify hundreds of targets for a single invocation. Thus, the resulting CHA call graph for the Android middleware is too large to be analyzed in a reasonable amount of time and memory [32].

To mitigate call graph bloat, we manually defined a list of classes and methods to exclude from the analysis, which become cutoff points in the call graph. We ensured that the class or method subject to exclusion did not contain, lead to, or was used in an authorization check. While the exclude list may require revision for newer versions of AOSP or modifications made by vendors, the creation of the exclude list is a largely one-time effort. Please see Appendix C for a detailed description of the exclusion procedure and our website [1] for a full list of excluded classes/methods.

Finally, when analyzing an entry point, ACMiner treats all other entry points as cutoff points in the call graph. This decision further reduces call graph bloat. Unfortunately, it also introduces unsoundness into the call graph, which we discuss in Section 7.

4.1.2 Identifying Authorization Check Statements. Once ACMiner has the call graph for all entry points, the next step is to identify authorization checks. As described in Section 2, the complete set of authorization checks is unknown. ACMiner takes a two pronged approach to identifying authorization checks. First, it identifies all possible checks leading to a protected operation (this section). Second, it refines the list of possible authorization checks based on code names and string values (Section 4.2). To describe this process, we must first define a *control predicate*.

Definition 1 (Control Predicate). A conditional statement (i.e., an *if* or *switch* statement) whose logic authorizes access to some protected operation.

Identifying protected operations is nontrivial, as they may range from accessing a device node to returning a private member variable. However, even if we knew the protected operations, we would still need to determine which conditional statements are control predicates. ACMiner uses the key observation that Android frequently throws a `SecurityException` when access is denied. Therefore, ACMiner marks all conditional statements on the control flow path between entry points and the statement throwing the `SecurityException` as *potential* control predicates.

While throwing a `SecurityException` is the most common way Android denies access, it is not the only way. Some entry points deny access by returning false or even by returning empty data. Such denials are not easily identifiable. Fortunately, as shown in Figure 1, Android often groups authorization checks into methods to simplify placement. We refer to such groups of authorization checks as *context queries*.

Definition 2 (Context Query). A method consisting entirely of a set of *control predicates*, calls to other *context queries*, and/or whose return value is frequently used as part of a *control predicate*.

By identifying *context queries*, ACMiner can mark control predicates not on the path between a entry point and a thrown `SecurityException`, thereby making the authorization check mining more complete. As shown in Figure 3, ACMiner is configured with an input file that specifies context queries. Our method for defining this input is described in Section 4.2.

Using these insights, ACMiner identifies authorization checks with fairly high accuracy. The identification procedure is as follows. First, ACMiner marks all conditional statements inside a context query and the subsequent transitive callees as control predicates for the entry point. Next, ACMiner performs a backwards inter-procedural control flow analysis from each statement throwing a `SecurityException` and each context query invocation to the entry point. During this backwards analysis, ACMiner marks all conditional statements on the path as potential control predicates. Finally, to capture control predicates that occur without a `SecurityException`, ACMiner performs a forward inter-procedural def-use analysis on the return value of a context query. During this analysis, ACMiner marks any conditional statement that uses the return value as a potential control predicate. Note, ACMiner does not currently track the return value through fields, as this was found to be too noisy. However, ACMiner can track the return value through variable assignments, arithmetic operations, array assignments, and the passed parameters of a method invoke.

4.1.3 *Representing Authorization Checks.* ACMiner represents the authorization checks for each entry point as a set of context queries and control predicates. We initially represented authorization checks as boolean expressions representing the control flow decisions that lead to a thrown `SecurityException` or invoked context query. This representation would allow ACMiner to verify the existence, order, and the comparison operators of the authorization checks. However, for complex services (e.g., the Activity Manager) this representation was infeasible due to the large number of authorization checks. Additionally, we found that without more complex context-sensitive analysis, ACMiner could not extract authorization checks involving implicit flows. Therefore, we simplified our consistency analysis to only consider *the existence* of an authorization check for an entry point. This approach requires two reasonable correctness assumptions: (1) all authorization checks have been placed and ordered correctly, and (2) all control predicates have the correct comparison operator. ACMiner cannot detect violations of these assumptions.

The existence of authorization checks is easily represented as a set; however some processing is required. For each variable in a authorization check statement, ACMiner must substitute all possible values for that variable. More specifically, for each control predicates and context queries statement (i.e., conditional or method invoke statement), ACMiner must generate a list containing the product of all the possible variables and the values for each variable. To reduce redundant output, ACMiner only computes the product for context queries that do not have a return value or whose return value is not used in a control predicates.

For this expansion, ACMiner applies an inter-procedural def-use analysis to each variable used in a statement, thereby obtaining the set of all possible values for that variable from the entry point to this specific use site. It then computes the product of these sets to achieve the complete set of authorization checks for a single statement. If a variable is assigned a value from the return of a method call, ACMiner does not consider the possible return values of the method, but instead includes a reference to all the possible targets of the method call. Similarly, if a variable is assigned a value from the field of a class or an array, ACMiner includes only a reference to the field or array instead of all the possible values that may be assigned to the field or array. As such, while the list of values largely consists of constants, it may also contain references to fields, methods and arrays. The resulting combination of all the iterations of values for each control predicate and each required context query of an entry point makes up the final set of authorization checks output by ACMiner.

The resulting set has the potential to be exponentially large. To prevent this growth and to remove noise in ACMiner’s output, we apply several simplifications to the authorization checks (see Appendix D). These simplifications are designed to increase the number of authorization checks that are equivalent from a security standpoint and in no way affect the completeness of the authorization checks.

4.2 Refining Authorization Checks

The techniques in Section 4.1.2 identify *potential* control predicates; however, not all conditional statements are authorization checks. Performing consistency analysis at this point would be infeasible

Table 1: Initial List of Context Queries

Classes	Methods
Context	enforcePermission
ContextImpl	enforceCallingPermission
ContextWrapper	enforceCallingOrSelfPermission
	checkPermission
	checkCallingPermission
	checkCallingOrSelfPermission
AccountManagerService	checkBinderPermission
LocationManagerService	checkPackageName
IActivityManager	checkPermission
ActivityManagerProxy	
ActivityManagerService	
ActivityManagerService	checkComponentPermission
ActivityManager	checkUidPermission
IPackageManager	checkUidPermission
IPackageManager\$Stub\$Proxy	checkPermission
PackageManagerService	

due to the excessive noise in the data. Therefore, ACMiner uses a one-time, semi-automated method to significantly reduce noise.

Our key observation is that Section 4.1 over approximates authorization checks on the path from entry points to a thrown `SecurityException` or context query. From this over-approximation, ACMiner can generate a list of all the strings and fields used in the conditional statements, a list of the methods whose return values are used in the conditional statements, and the methods containing the conditional statements. These values can be manually classified as authorization-related or not. The general refinement procedure is as follows: (1) a domain expert filters out values not related to authorization; (2) the refined list is translated into generalized expressions; (3) ACMiner uses the generalized expressions to automatically filter out values not related to authorization; (4) the generalized expressions are refined until the automatically generated list is close to that defined by the domain expert. While creating generalized expressions is time consuming, they can be used to analyze multiple Android builds with minimal modifications.

The specific refinement procedure is divided into two phases: (§4.2.1) identifying additional context queries, and (§4.2.2) refining control predicate identification.

4.2.1 *Identifying Additional Context Queries.* ACMiner uses context queries as indicators of the existence of authorization checks when no `SecurityException` is thrown. Our initial list of *context queries*, shown in Table 1, was very limited and only contained 33 methods. To expand this list we performed the following steps: (1) run ACMiner as described in Section 4.1 using the initial list of *context queries*, (2) from the marked conditional statements, generate a list of the methods containing these conditional statements and the methods whose return values are used in these conditional statements, (3) have a domain expert inspect the list and identify methods that match our definition of a context query, and add these to our list of context queries, and (4) repeat steps 1→3 until no new context queries are added to the list. For Android AOSP 7.1.1, this procedure took about 48 hours and increased the number of *context queries* to 620 methods.

To make this list reusable, we translate it into a set of generalized expressions that describe context queries across different Android versions. The expressions consist of regular expressions and string matches for the package, class, and name of a method, and also include conditional logic. An example expression is shown in Figure 4. Overall, we defined 49 generalized expressions to describe context queries for Android AOSP 7.1.1, which took <10 hours. The expressions enabled ACMiner to identify an additional 255 methods,

```
(and (or (starts-with-package android.)
         (starts-with-package com.android.))
      (regex-name-words `*(enforce|has|check)\s
                        ([a-z]+)?permission(s)?\b`*)
      (not (equal-package android.test))...))
```

Figure 4: Example expressions to describe context queries.

resulting in a total of 875 context queries. Please see Appendix E for details on the translation procedure and our website [1] for the expression-list.

4.2.2 *Refining Control Predicate Identification.* To refine the over-approximation of authorization checks, ACMiner again uses a semi-automated method of refinement, this time for control predicates. The process begins by running ACMiner with the refined context queries from Section 4.2.1. The expert then inspects lists of strings, fields, and methods for the *potential* control predicates, removing those not related to authorization.

From our exploration, we discovered a number of different categories of control predicates. Some we were aware of such as those involving *UID*, *PID*, *GID*, *UserId*, *ApplId*, and package name. However, even within these categories, we discovered new fields, methods, and contexts in which checks are performed. We also discovered previously unknown categories of control predicates including those: (1) involving *SystemProperties*, (2) involving flags, (3) performing permission checks using the string equals method instead of the standard check permission methods, (4) checking for specific intent strings, and (5) checking boolean fields in specific classes. Finally, we discovered that a significant amount of noise was generated by the conditional statements of loops and sanity checks such as *null* checks. Using all of the information gained from the exploration of elements related to possible *control predicates*, we defined a filter that refines control predicate and reduces the overall noise.

Overall, the exploration took about 56 hours. We defined a 41-rule filter in about 16 hours (see our website [1] for the actual filter and Appendix F for the specification process). The application of the filter for Android AOSP 7.1.1 reduced what ACMiner considered to be control predicates from 25808 to 3308. Such a significant reduction not only underscores the need for a filter but also makes the consistency analysis (Section 4.3) more feasible.

4.3 Consistency Analysis

The final step of ACMiner is consistency analysis of authorization checks for each entry point. In this paper, we perform consistency analysis of all entry points within a service. However, the methodology may work across multiple services, or even across different OEM firmwares. ACMiner performs consistency analysis by automatically discovering underlying correlative relationships between sets of authorization checks. Specifically, ACMiner adopts a targeted approach for association rule mining by using constraint-based querying. It then uses these association rules to predict whether an entry point’s authorization checks are consistent. The results are presented to a domain expert for review.

Figure 5a shows an example association rule generated by ACMiner from the code in Figure 1. X and Y are sets of authorization checks found in entry points. The rule states that if an entry point has check(s) from the set X , then it must also have the check(s) in set Y . ACMiner then uses these generated rules to identify potential vulnerabilities by reporting entry points that violate the learned

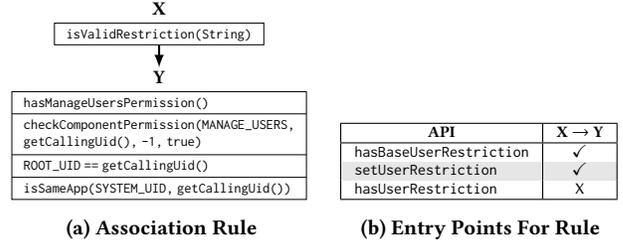


Figure 5: (a) shows an association rule generated from the code in Figure 1 and (b) illustrates how the first 2 entry points satisfy the rule, while *hasUserRestriction* does not, indicating it contains one or more inconsistent authorization checks.

rules (i.e., if an entry point has all of the checks in X , but it is missing checks in Y , then a violation occurs). For instance, Figure 5b shows the three entry points that match X for the rule in Figure 5a, out of which *hasUserRestriction* fails to satisfy the rule (it does not contain *checkManageUsersPermission*). On closer inspection, we discovered that all three entry points either set or get information about user restrictions. Moreover, the functionality of *hasUserRestriction* is nearly identical to *hasBaseUserRestriction*, which suggests *checkManageUsersPermission* is needed. As seen in these examples, ACMiner allows an expert to only compare entry points that are close in terms of their authorization checks, which is more precise than comparing all entry points to one another.

The remainder of this section discusses ACMiner’s approach to efficiently discover these association rules and how ACMiner uses them to detect inconsistencies in authorization checks.

4.3.1 *Association Rule Mining.* Association rule mining discovers correlative relationships between sets of authorization checks, $A = \{i_1, i_2, \dots, i_n\}$, across a set of entry points, $E = \{t_1, t_2, \dots, t_m\}$ where each entry point in E contains a subset of the items in A . An association rule takes the form $X \implies Y$ where X (antecedent) and Y (consequent) are sets of authorization checks and X and Y are disjoint, i.e., $X \subseteq A$ and $Y \subseteq A$ and $X \cap Y = \emptyset$.

To avoid an excessive number of association rules, ACMiner uses two statistical constraints (support and confidence) to remove candidate association rules that are less than the thresholds minimum support (*minsup*) and minimum confidence (*minconf*). Let $\alpha(I)$ represent the set of entry points in E that contain the authorization checks $I \subseteq A$, i.e., $\alpha(I) = \{t \in E \mid \forall i \in I, i \in t\}$. The support of an association rule $X \implies Y$ is the probability that a set of authorization checks $Z = X \cup Y$ appears in the set of transactions E , i.e., $\sigma(Z) = \frac{|\alpha(Z)|}{|E|}$. The confidence of an association rule is an estimate of the conditional probability of the association rule $P(Y|X)$ where $X \implies Y$ and can be calculated as $conf(X \implies Y) = \frac{\sigma(X \cup Y)}{\sigma(X)}$.

While association rule mining has been applied to similar problems by prior work [29], the large transaction size (i.e., number of authorization checks in an entry point) in our problem domain makes general association rule mining algorithms infeasible due to their exponential complexity. Therefore, ACMiner uses two main optimizations to reduce the complexity to polynomial time.

First, ACMiner only generates a subset of the association rules called closed association rules [41]. An association rule $X \implies Y$ is closed if $X \cup Y$ is a frequent closed itemset. A frequent closed

itemset is a set of authorization checks $C \subseteq A$ where the support of C is greater than *minsup* and there does not exist a superset C' that has the same support as C . C is closed iff $\beta(\alpha(C)) = C$ where $\beta(T)$ represents the largest set of common authorization checks present in the entry points T where $T \subseteq E$, i.e., $\beta(T) = \{i \in A \mid \forall t \in T, i \in t\}$. Note that only mining frequent closed itemsets is lossless, because all frequent itemsets can be generated from the set of frequent closed itemsets, as proven by Zaki and Hsiao [46]. Our proof that closed association rules also do not result in information loss can be found in Appendix G.

Second, ACMiner generates closed association rules in a targeted manner by placing constraints on the authorization checks that appear in the antecedent of the association rule. Since the goal of consistency analysis is to predict whether an entry point's implementation of authorization checks is consistent, we are only interested in generating association rules where the antecedent of the association rule is a subset of the entry point's authorization checks (i.e., $X \subseteq A_j$ where A_j is the authorization checks of entry point e_j). For example, consider $A_j = \{i_1, i_2, i_3\}$ and we have two frequent closed itemsets $\{i_1, i_2, i_3, i_4\}$ and $\{i_5, i_6, i_7\}$. The association rule $\{i_1, i_2, i_3\} \implies i_4$ is useful, as it could potentially hint that the authorization checks in A_j is inconsistent and should also contain i_4 . However, all of the association rules from the set $\{i_5, i_6, i_7\}$ do not provide additional information on the consistency of authorization checks in A_j , as the two sets are disjoint.

Further, assuming that the authorization checks that are present within an entry point are correct, we can force the antecedent to be constant. In particular, when generating association rules from a frequent closed itemset I for an entry point A_j , we set $X = A_j \cap I$ and can generate association rules by varying the items in Y . If we reduce the authorization checks in X , then we are making the rule less relevant to the consistency of the entry point A_j while keeping X constant only produces the most relevant association rules.

4.3.2 Inconsistency Detection and Output Generation. ACMiner uses the association rules discussed in Section 4.3.1 to analyze the consistency of an entry point's authorization checks. To minimize the amount of manual effort required to verify the presence of an inconsistency, we ensure the output only contains high confidence rules by setting *minconf* to 85%. Moreover, as we want the authorization checks in the consequent of an association rule to be formed by at least 2 entry points, we set the *minsup* to $\frac{2}{|E|}$.

While generating the association rules, we mark an entry point's authorization checks as consistent if there exists a frequent closed itemset that contains the exact same authorization checks as the entry point, as this hints that the entry point's authorization checks are consistent with another entry point's authorization checks. In particular, entry point e_j 's authorization checks A_j is consistent iff $\exists C \in A \mid C = A_j \wedge \beta(\alpha(C)) \wedge \sigma(C) \geq \frac{2}{|E|}$. In contrast, we mark an entry point's authorization checks as potentially inconsistent if an association rule exists where the entry point's authorization checks are the antecedent of the rule and the consequent is not empty (i.e., $\exists X \implies Y \mid X \subseteq A_j \wedge Y \neq \emptyset$).

ACMiner outputs an HTML file for the domain expert to review for each association rule representing a potentially inconsistent entry point. The HTML file contains the set of supporting authorization checks for the association rule (i.e. the antecedent), the set

of authorization checks being recommended by the association rule (i.e. the consequent), and the 3 or more entry points that contain the authorization checks of the association rule. This group of entry points can be subdivided into two sets: the target entry point and the supporting entry points. The target entry point is the entry point the association rule has identified as being inconsistent, i.e., the entry point the association rule is recommending additional authorization checks for. The supporting entry points are the 2 or more entry points where the recommended authorization checks occur. Note that the supporting authorization checks occur in both the target and the supporting entry points. To aid the review, the HTML file also contains the set of all authorization checks from the target entry point that do not occur in the supporting authorization checks and for all authorization checks, the method in the Android source code where the checks occur.

To reduce the manual effort required to confirm inconsistencies, we perform two post-processing techniques. First, we remove association rules where $|recommended\ authorization\ checks| \geq 5 * |supporting\ authorization\ checks|$, since association rules that contain 100 authorization checks which imply 500 authorization checks is improbable. Second, we remove any remaining association rules that have over 100 recommended authorization checks as such association rules are unlikely to indicate inconsistencies, and the domain expert may not be able to evaluate such rules in a reasonable amount of time.

5 EVALUATION

We evaluated ACMiner by performing an empirical analysis of the system services in AOSP version 7.1.1_r1 (i.e., API 25) built for a Nexus 5X device. Our analysis was performed on a machine with an Intel Xeon E5-2620 V3 (2.40 GHz), 128 GB RAM, running Ubuntu 14.04.1 as the host OS, OpenJDK 1.8.0_141, and Python 2.7.6.

We used ACMiner to mine the authorization checks of all the entry points from this build of AOSP and perform consistency analysis, as described in Section 4. Finally, we manually analyzed the inconsistencies using a systematic methodology to identify high risk (i.e., easily exploitable) and high impact vulnerabilities, and developed proof-of-concept exploits to validate our findings. Our evaluation is guided by the following research questions:

- RQ1** Does ACMiner reduce the effort required by the domain expert in terms of the entry points that need to be analyzed?
- RQ2** Do the inconsistencies identified by ACMiner help a domain expert in finding security vulnerabilities?
- RQ3** What are the major causes behind inconsistencies that do not resolve to security vulnerabilities?
- RQ4** Is ACMiner more effective than prior work at detecting vulnerabilities in system services?
- RQ5** What is the time required by ACMiner to analyze all the system services in a build of Android?

We now highlight the salient findings from our evaluation, followed by the categorization of the discovered vulnerabilities. The categorization of non-security inconsistencies, developed via a systematic manual analysis of our results, is described in Section 6.

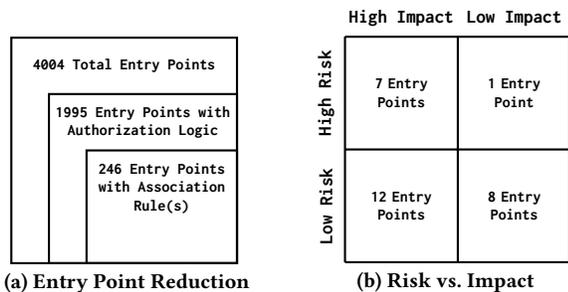


Figure 6: (a) shows how ACMiner is able to reduce the scope of the AOSP 7.1.1 system code a domain expert needs to evaluate and (b) breaks down the 28 vulnerabilities in terms of risk and impact.

5.1 Evaluation Highlights

As shown in Figure 6a, ACMiner reduces the total number of entry points that need to be manually analyzed down to just 246 entry points with inconsistent authorization checks, a 94% reduction (RQ1). As a result, ACMiner significantly enhances a domain expert’s ability to evaluate the consistency of access control enforcement in the Android system by minimizing the effort required. Further, ACMiner took approximately 1 hour and 16 minutes to mine the authorization checks of all entry points from the system image of the AOSP build, and spent an additional 30 minutes producing the HTML files for the association rules that represent potentially vulnerable entry points. While ACMiner could be optimized further, time taken by ACMiner is a feasible cost, given its scalability benefits over a fully manual analysis (RQ5).

On manually analyzing the 246 entry points, we discovered a total of 28 entry points containing security vulnerabilities (RQ2). As Figure 6b illustrates, these 28 vulnerabilities were then classified in terms of their risk (i.e., the ease of exploiting a vulnerability) as well as the impact (i.e., the gravity of the consequence of an exploited vulnerability). Using this criteria, we found 7 vulnerabilities that were high risk as well as high impact, 1 vulnerability that was high risk only, 12 vulnerabilities that were high impact only, and 8 vulnerabilities that were low in terms of both risk and impact. All 28 vulnerabilities have been submitted to Google. So far, 2 of our vulnerabilities have been assigned a “moderate” Android Security Rewards (ASR) severity level, which is generally awarded to bypasses in access control mechanisms (e.g., restrictions on constrained processes, or general bypasses of privileged processes [23]). In Section 5.2, we categorize these 28 vulnerabilities according to their effect; however, we only discuss a few of these vulnerabilities in depth, due to space constraints.

ACMiner is significantly more effective than prior work at identifying inconsistent authorization checks. For instance, ACMiner is able to identify 875 unique context queries using the semi-automated approach described in Section 4.2.1, a drastic 2552% improvement over the original 33 context queries that encompass a majority of the context queries considered by Kratos [39]. Further, while AceDroid [2] is more comprehensive than Kratos in its identification of Android’s authorization checks, it relies on a manually defined list of context queries, which is insufficient. That is, as described in Section 4.2.1, our thorough attempts at identifying context queries through manual observation alone resulted in the identification of only 620 context queries, 71% of the total context queries that

ACMiner is able to find using its semi-automated approach. Thus, while AceDroid does not provide quantitative information on its set of context queries, we can certainly say that it is not as complete as ACMiner in its identification of Android’s authorization checks. Indeed, the context query `isValidRestriction` in Figure 1 is an example of a context query that neither AceDroid nor Kratos was able to identify, and in fact, one that we missed in our manual definition of Android’s authorization checks. However, through the general expressions, ACMiner was able to identify `isValidRestriction` as a context query and the vulnerability outlined in Figure 1. Moreover, neither AceDroid nor Kratos makes any mention of the App Ops restrictions in their definition of Android’s authorization checks. Yet ACMiner is able to identify 2 vulnerabilities relating to the App Ops restrictions (see Section 5.2). While a full empirical comparison with Kratos and AceDroid is infeasible due to the lack of source code access, our evaluation demonstrates that ACMiner makes significant advancements to existing work in terms of the coverage of the authorization checks, making the consistency analysis as complete as possible (RQ4).

Finally, ACMiner produced 453 association rules denoting inconsistent authorization checks in 246 entry points. Some entry points had more than one inconsistency. Furthermore, while some inconsistencies were indeed valid security vulnerabilities (30/453), others were a result of irregular coding practices in Android (25/453) or indicative of ACMiner’s limitations in terms of analyzing the semantics of the authorization checks (RQ3). The limitations identified via our analysis point to hard problems in analyzing Android’s access control logic and motivate future work.

5.2 Findings

Table 2 describes the vulnerabilities discovered through our analysis of Android 7.1.1 with ACMiner. On manually analyzing the inconsistent entry points produced by ACMiner, we discovered 28 entry points that represent security vulnerabilities. While most of these entry points represent one vulnerability each, two entry points (i.e., `getLastLocation` and `setStayOnSetting`, vulnerabilities 15 and 16 in Table 2 respectively) each led us to clusters of multiple identically vulnerable entry points, as described later in this section. For simplicity, we count each cluster as a single vulnerability.

We group the vulnerabilities into the following 3 categories: (1) user separation and restrictions, (2) App Ops, (3) and `pre23`. This categorization is based on the subsystems affected by the vulnerabilities (e.g., App Ops), as well as the characteristics they have in common (e.g., `pre23`). Additionally, some vulnerabilities that are hard to classify have been categorized as (4) miscellaneous. **VC1: Multi-user Enforcement:** As shown in Table 2, a majority (i.e., 14) of the vulnerabilities affect Android’s separation among users (i.e. user profiles in Android’s multi-user enforcement [24]). These can be further divided into four subcategories based on how they may be exploited: (1) leaking user information across users, (2) operating across users, (3) modifying user settings before a user exists, and (4) allowing users to bypass restrictions.

1. *Leaking Information to Other Users:* In 5 entry points (i.e., 1→5 in Table 2), the lack of checks leads to potential leaks of security-sensitive information to other users. For instance, using the vulnerable entry point `getInstalledApplications` in the `PackageM-`

Table 2: Description of vulnerabilities, along with the services in which they are present

Associated Entry Point (Service)	Vulnerability Description
VC1: Multi-user Enforcement	
1. getInstalledApplications (PMS)	Missing the enforceCrossUserPermission check, allowing any app on one user profile to discover apps installed on other profiles.
2. getPackageHoldingPermissions (PMS)	Missing enforceCrossUserPermission, allowing any app on one user profile to get sensitive permission information about other profiles.
3. hasUserRestriction (UMS)	Missing the hasManageUsersPermission check, which checks for the permission MANAGE_USERS, is missing, allowing any user to discover the restrictions on their own and other user profiles.
4. checkUriPermission (AMS)	Missing the handleIncomingUser check that verifies if a user can operate on behalf of another, allowing any user access to content provider URIs belonging to another user, so long as the app making the request has access to the content provider.
5. grantUriPermission (AMS)	Missing the handleIncomingUser check, with similar implications as checkUriPermission.
6. killPackageDependents (AMS)	Missing the handleIncomingUser check, allowing any user to kill the apps and background processes of another user.
7. setUserProvisioningState (DPMS)	Missing the enforceFullCrossUsersPermission check, enabling any user to change another user profile's state.
8. setDefaultBrowserPackageName (PMS)	Missing the enforceCrossUserPermission check, enabling any user to set the default browser of any other user.
9. updateLockTaskPackages (AMS)	Missing handleIncomingUser, enabling any user to modify the apps that may be permanently pinned to the screen in a kiosk like venue.
10. installExistingPackageAsUser (PMS)	Does not check if the target user exists, allowing any user to install apps on user profiles that may be created at a later time.
11. setApplicationHiddenSettingAsUser (PMS)	Does not check if the target user exists, allowing any user to hide apps on user profiles that may be created in the future.
12. setAlwaysOnVpnPackage (CS)	Does not check for the no_config_vpn user restriction, allowing a managed user to set its always on VPN to another application.
13. setWallpaperComponent (WPMS)	Missing the two checks isSetWallpaperAllowed and isWallpaperSupported, allowing a managed user to change their wallpaper.
14. startUpdateCredentialsSession (ACMS)	Missing checks canUserModifyAccounts and canUserModifyAccountsForType, allowing a user to trigger an update for the credentials of online accounts like Google and Facebook even when restricted.
VC2: App Ops	
15. noteProxyOperation (AOMS)	Missing the verifyIncomingUid check, which checks for a signature permission, allowing non-system apps to call this entry point.
16. getLastLocation (LMS)	A majority of the entry points in the LMS use the AppOpsManager check checkOp, which is not intended for security, instead of the security check noteOp. getLastLocation uses the correct check.
VC3: Pre23	
17. setStayOnSetting (POMS)	On systems with API 23 or above, the pre23 protection level allows any permission to be automatically granted to non-system apps built targeting the API 22 or below. This vulnerability allows non-system apps to access 6 additional entry points protected by the WRITE_SETTINGS signature permission, as WRITE_SETTINGS also has the pre23 protection level.
VC4: Miscellaneous	
18. unbindBackupAgent (AMS)	Missing check for if caller is performing a backup, allowing any app to disrupt the backup process of another app.
19. getPersistentApplications (PMS)	Missing system UID check, allowing any non-system app to discover what apps and services permanently run in the background.
20. logEvents (MLS)	Incorrect check for permission CONNECTIVITY_INTERNAL, should check DUMP when writing sensitive data to logs.
21. getMonitoringTypes (GHS)	Missing check checkPermission, allowing a caller access both fine and coarse levels of geofence location data.
22. getStatusOfMonitoringType (GHS)	Missing check checkPermission, with similar implications as getMonitoringTypes.
23. setApplicationEnabledSetting (PMS)	Missing isPackageDeviceAdmin check, allowing an app to disable an active administrator app.
24. setComponentEnabledSetting (PMS)	Missing isPackageDeviceAdmin check, allowing an app to disable components of an active administrator app.
25. convertFromTranslucent (AMS)	Missing check for enforceNotIsolatedCaller, allowing a isolated process to affect the transparency of windows.
26. notifyLockedProfile (AMS)	Missing check for enforceNotIsolatedCaller, allowing an isolated process to trigger a return to the home screen.
27. setActiveScorer (NSS)	Missing BROADCAST_NETWORK_PRIVILEGED permission check which is always paired with the SCORE_NETWORKS permission check.
28. getCompleteVoiceMailNumberForSubscriber (PSIC)	Incorrect check for permission CALL_PRIVILEGED instead of the READ_PRIVILEGED_PHONE_STATE results in coarse-grained enforcement.

AMS=ActivityManagerService; AOMS=AppOpsManagerService; CS=ConnectivityService; DPMS=DevicePolicyManagerService; LMS=LocationManagerService; PMS=PackageManagerService; POMS=PowerManagerService; UMS=UserManagerService; WPMS=WallpaperManagerService; PSIC=PhoneSubInfoController; ACMS=AccountManagerService; MLS=MetricsLoggerService; GHS=GeofenceHardwareService; NSS=NetworkScoreService

anagerService, any user can learn of the applications another user has installed, as the entry point does not enforce any checks other than checking if the user being queried exists. Similarly, the entry point hasUserRestriction in the UserManagerService, previously used as the motivating example, is not protected with the signature level permission MANAGE_USERS, which is present in the similar hasBaseUserRestriction entry point. This omitted authorization check allows a user to know of the restrictions placed on other users, which is security-sensitive information that should not be public. The entry points getPackageHoldingPermissions, checkUriPermission and grantUriPermission similarly leak sensitive information.

We experimentally confirmed the existence of both the vulnerabilities in hasUserRestriction and getInstalledApplications in Android 7.1.1 as well as Android 8.1. We have submitted bug reports to Google and received "moderate" ASR severity level for both the bugs. Further, we confirmed that the vulnerability in getPackageHoldingPermissions was fixed in Android 8.1. As a result, we could not submit it to Google's bug program, which only considers bugs affecting the latest version of Android. All remaining vulnerabilities have been reported to Google.

2. *Operating Across Users:* Missing authorization checks in 4 entry points (i.e., 6→9 in Table 2) allow users to bypass multi-user restrictions and perform sensitive operations on behalf of other

users. For example, we discovered that the entry point killPackageDependents takes in a *userId* as an argument but does not actually verify whether the calling user is allowed to perform operations on behalf of the supplied *userId*. This allows *any user to kill the apps and background processes of any other user*. A similar flaw in entry point setUserProvisioningState enables any user to set the state of any other user profile to states such as "managed", "unmanaged", or "finalized". Such changes may be dangerous. For instance, a user may be able to set their managed enterprise profile to unmanaged, releasing it from the administrator's control.

Fortunately, all four entry points described in this category can only be called from apps installed on the system image (i.e., are protected by authorization checks that ensure this). This indirectly mitigates some damage, by making the vulnerabilities difficult to exploit from a third-party app. However, capability leaks in privileged apps may allow such vulnerabilities to be exploited by third-party apps, as prior work has demonstrated [25, 44]. All of these vulnerabilities have been reported to Google.

3. *Modifying User Settings Before A User Exists:* Both the entry points installExistingPackageAsUser and setApplicationHiddenSettingAsUser do not perform the authorization check exists, which verifies if a the *userId* passed into the entry points represents a valid user. Without this check, it is possible for a caller to install an app

```

1  /** Do a quick check for whether an application might be
2  * able to perform an operation. This is not a security
3  * check; you must use noteOp or startOp for your actual
4  * security checks, which also ensure that the given uid
5  * and package name are consistent. ... */
6  int checkOp(int op, int uid, String packageName) {...}

```

Figure 7: The comment above checkOp from the class AppOpsManager that states it should not be used as a security check.

for a non-existent user or hide an app from a non-existent user. Thus, when the user for whom this change was made is actually created, these settings will already be in place. These entry points are only callable from systems apps; however, system apps may be compromised or may leak capabilities, and the *exists* check needs to be in place to prevent system apps from being tricked into allowing users to install apps in profiles that have yet to be created (e.g., installing apps in a future enterprise profile). We have submitted these vulnerabilities to Google.

4. Allowing Users to Bypass Restrictions: Vulnerabilities in entry points 12→14 from Table 2 allow a user to perform operations despite the restrictions placed on the user profile. For instance, the entry point `setAlwaysOnVpnPackage` does not check for the restriction `no_config_vpn`, allowing a managed user to set the always on VPN for the user profile to another application, effectively switching VPN connections. The entry points `setWallpaperComponent` and `startUpdateCredentialsSession` have similar vulnerabilities. All of these vulnerabilities have been reported to Google.

VC2: App Ops: ACMiner identified weaknesses related to App Ops. One such vulnerability lies in the `noteProxyOperation` of the `AppOpsService`. The entry point makes a note of an application performing some operation on behalf of some other application through IPC. However, unlike other entry points in the `AppOpsService`, `noteProxyOperation` is missing the authorization check `verifyIncomingUid` which includes a check for the *signature* level permission `UPDATE_APP_OPS_STATS`. Without `verifyIncomingUid`, it is possible for any non-system app to use `noteProxyOperation` to query the restrictions a user has placed on other apps, thus retrieving information that should not be available to non-system apps.

We discovered a set of identical vulnerabilities in App Ops through our analysis of the `getLastLocation` entry point in the `LocationManagerService`, which ACMiner pointed out as having inconsistent authorization checks. The `getLastLocation` entry point calls the authorization check `reportLocationAccessNoThrow` which performs the check `noteOpNoThrow` from the `AppOpsManager`, a wrapper for the `AppOpsService`. ACMiner correctly identified the use of `noteOpNoThrow` as an inconsistency since a majority of the entry points (9) in `LocationManagerService` use the authorization check `checkLocationAccess` which performs the check `checkOp` from the `AppOpsManager`. However, as Figure 7 shows, the comment above the `checkOp` method clearly states that `checkOp` should not be used to perform a security check. Instead, one of the various forms of `noteOp` should be used. This implies that all 9 entry points using the context query `checkLocationAccess` suffer from a vulnerability, and that the use of `reportLocationAccessNoThrow` in `getLastLocation` is actually appropriate. This instance demonstrates an interesting outcome of the use of consistency analysis in ACMiner. That is, our use of consistency analysis in ACMiner is also useful in identifying instances, where the majority of the related entry points are

```

<permission android:name="android.permission.WRITE_SETTINGS"
android:protectionLevel="signature|preinstalled|appop|pre23" />

```

Figure 8: The permission protection levels of WRITE_SETTINGS in the AndroidManifest.xml file [3]

vulnerable. As described previously, for simplicity, we count this cluster of vulnerable entry points as a single vulnerability, which has been submitted to Google.

VC3: Pre23: ACMiner identified a group of vulnerabilities related to Android’s *pre23* permission protection level. The entry point `setStayOnSetting` in the `PowerManagerService` uses the authorization check `checkAndNoteWriteSettingsOperation`, which checks if an app has the *signature* level permission `WRITE_SETTINGS`. Permissions with the *signature* protection level can only be granted to system apps (i.e., apps that were originally packaged with the system image). However, as shown in Figure 8, `WRITE_SETTINGS` has an additional protection level of *pre23*, which has an interesting effect on Android versions 6.0 or above (i.e., API 23 or above). It allows permissions marked as *pre23* to be granted to non-system apps that target API 22 or below [22]. Thus, as a result of the improperly defined permission protection levels for `WRITE_SETTINGS`, the *pre23* grants non-system apps access to a signature level permission.

The damage resulting from the *pre23* vulnerability is not restricted to the entry point `setStayOnSetting`. A simple search for the use of the permission `WRITE_SETTINGS` in the authorization checks ACMiner mined for all entry points in the system revealed 13 additional entry points checking for the permission `WRITE_SETTINGS`, 6 of which can be called from a non-system app using the *pre23* vulnerability (i.e., these 6 entry points are not protected with any other *signature* permission). Of the 6, the following 5 entry points deal with tethering and are located in the `ConnectivityService`: `setUsbTethering`, `stopTethering`, `startTethering`, `tether`, and `untether`. The last `setWifiApEnabled` was located in the `WifiServiceImpl` and allows a caller to set some WIFI access point configuration, causing the device to connect or disconnect from any WIFI access point the caller provides. These entry points are clearly more important to protect than `setStayOnSetting`, and an adversary may be able to do considerable damage by exploiting them. We do not count these entry points in our initial list of 28 vulnerabilities. All entry points affected by the *pre23* vulnerability have been submitted to Google.

VC4: Miscellaneous Vulnerabilities: ACMiner also identified 11 vulnerabilities related to information leaks, denial of service, disabling of administrator apps, and a mixture of other minor vulnerabilities. All of these vulnerabilities have been reported to Google.

6 NON-SECURITY INCONSISTENCIES

ACMiner identified 423 inconsistencies (i.e., rules) that did not represent vulnerabilities. Aside from the 20 rules that were caused by easily fixed bugs in ACMiner, we resolve these non-security inconsistencies to their likely causes, and classify them into 9 categories, shown in Table 3 (RQ3). The first three categories point to irregular coding practices, i.e., (1) inconsistent application of short-cuts to speed up access, (2) access bugs or discrepancies in how the permission should be used as per the documentation, or (3) inconsistent application of hard-coded checks that would potentially lead to vulnerabilities on future updates. The remaining 6 categories point to issues that could be corrected by engineering improvements to

Table 3: Non-security Inconsistencies

Type of Inconsistency	Number of Rules
1. Shortcuts to Speed-Up Access	7
2. Fixing Access Bugs	2
3. Potential Vulnerabilities	16
4. Difference in Functionality	189
5. Checks With Different Arguments	66
6. Noise in Captured Checks	53
7. Restricted to Special Callers	37
8. Semantic Groups of Checks	23
9. Equivalent Checks	10

ACMiner, such as considering semantic equivalence between authorization checks, or the integration of call graph comparison and method-name comparison to mitigate the analysis of functionally different entry points. We provide additional details on all of the 9 categories in Appendix H.

7 LIMITATIONS

While ACMiner is effective at discovering inconsistencies that lead to vulnerabilities, consistency analysis has a general limitation, i.e., it may not discover vulnerabilities that are consistent throughout code. Further, for precision, ACMiner does not handle the invocation of secondary entry points, i.e., calls to entry points from within other entry points. ACMiner omits the *ordering* of the authorization checks and hence does not identify improper operator use in *control predicates*, which we plan to explore in the future. Moreover, ACMiner’s semi-automated analysis requires the participation of domain experts. However, as Section 5 demonstrates, our design significantly reduces manual effort in contrast with the manual validation of system services. As we have already analyzed AOSP version 7.1.1, only minor input is needed to analyze newer versions or vendor modifications. Finally, ACMiner shares the general choices made by Android static analysis techniques for precision, i.e., it does not consider native code, or runtime modifications (e.g., reflection, dynamic code loading, Message Handlers).

8 RELATED WORK

ACMiner addresses a problem that has conceptual origins in prior work on authorization hook validation for traditional systems. Early investigations targeted the Linux Security Modules (LSM) hook placement in the Linux kernel, using techniques such as type analysis using CQUAL [48], program dominance [49], and dynamic analysis to create authorization graphs from control flow traces [13, 30]. As the lack of ground truth is a general challenge for hook validation, prior work commonly uses consistency analysis [13, 30, 42]. Closest to our work is AutoSES [42], which infers security specifications from code bases such as the Linux kernel and Xen. However, AutoSES assumes a known set of security functions or security-specific data structures, whereas ACMiner identifies a diverse set of authorization checks in the Android middleware.

The closest to our approach is prior work on authorization hook validation in the Android platform, i.e., Kratos [39] and AceDroid [2]. ACMiner distinguishes itself from Kratos and AceDroid through its deep analysis of Android’s system services, and its significantly improved coverage of Android’s authorization checks.

Kratos [39] compares a small subset of Android’s authorization checks across entry points of the same system image to look for inconsistent checks between different system services. ACMiner does not analyze for consistency across services. Instead, we hypothesize

that entry points within a single service are similar in purpose, and hence, analyze the consistency of the authorization checks by comparing the entry points of every system service with other entry points in the same service. Further, ACMiner’s semi-automated approach for identifying authorization checks results in a 2552% improvement over Kratos’ manually-curated list (Section 5).

Similarly, AceDroid [2] evaluates the consistency of the authorization checks among different vendor-modified Android images, and hence differs from ACMiner in terms of its objective. AceDroid makes key improvements over Kratos, as it considers various non-standard context queries not considered by Kratos. However, AceDroid also relies on a manually-defined list of context queries, which may produce only approximately 71% of the context queries that ACMiner is able to find (Section 5). While a quantitative comparison with Kratos and AceDroid is difficult due to the unavailability of code/data, this qualitative comparison demonstrates the remarkable improvements made by ACMiner’s novel techniques.

Finally, recent literature is rich with static and dynamic program analysis of third-party Android apps targeted at privacy infringement [14, 21, 27], malware [18, 28, 47], as well as vulnerabilities [10, 15]. As the Android platform and apps use similar programming abstractions, researchers have applied these tools and techniques to the platform code, e.g., for providing a mapping between APIs and corresponding permissions [5, 9, 19] or automatically identifies privacy-sensitive sources and sinks [4]. Moreover, prior work has also studied the platform code, to analyze OEM apps for capability leaks (e.g., Woodpecker [25] and SEFA [44]), discover privilege escalation on update vulnerabilities (e.g., Xing et al. [45]), or uncover gaps in the file access control policies in OEM firmware images (e.g., Zhou et al. [50]). While ACMiner shares a similar objective, unlike prior work, ACMiner provides an automated and systematic investigation of core platform services.

9 CONCLUSION

This paper provides an approach for the systematic and in-depth analysis of a crucial portion of Android’s reference monitor, i.e., its system services. We design ACMiner, a static analysis framework that comprehensively identifies a diverse array of authorization checks used in Android’s system services, and then adapts the well-founded technique of association-rule mining to detect inconsistent access control among service entry points. We discover 28 security vulnerabilities by analyzing AOSP version 7.1 using ACMiner, and demonstrate significantly higher coverage of checks than the state of the art. Our work demonstrates the feasibility of in-depth analysis of Android’s system services with ACMiner, as it significantly reduces the number of entry points that must be analyzed, from over 4000 with millions of lines of code to a mere 246.

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A EXTRACTING JAVA CLASS FILES

ACMiner first obtains the Java class files for the desired version of Android. Soot analyzes Java programs by translating their code

into its own Java code representation (i.e., Jimple). It parses *.class*, *.java*, *.jimple*, and *.jar* files. The recent incorporation of Dexpler [8] into Soot adds support for *.dex* files and *.jar* files containing *.dex* files (i.e., *.apk* files).

ACMiner is designed to analyze both AOSP and OEM builds of the Android middleware. As such, ACMiner must process Android’s *system.img* and extract the class files. If the *system.img* contains *.odex* or *.oat* files, ACMiner decompiles and recompiles them into *.dex* using baksmali/smali [26]. As shown in Figure 3, ACMiner automates this process and outputs a *.jar* file containing all the class files of the Android middleware in Soot’s Jimple format. This *.jar* containing Jimple files is then used on all subsequent runs of ACMiner. This pre-processing can take upwards of 20 minutes and saves unnecessary re-computation.

B EXTRACTING SYSTEM SERVICES AND ENTRY POINTS

Android’s middleware is largely composed of isolated services that only communicate through predefined Binder boundaries. This division allows each service to be analyzed separately, and to define each service by the code reachable through its Binder entry points. ACMiner extracts system services and their entry points similar to PScout [5], Kratos [39], and AceDroid [2].

Specifically, ACMiner uses Soot’s class hierarchy information to find all classes that: (1) are subclasses of `android.os.Binder` and (2) implement the `onTransact` method. Next, ACMiner identifies the signatures of the handler methods that `onTransact` methods call. Our insight is that all such methods are invoked on the same receiver object (i.e., *this*). Note that handler methods need not be implemented in the *stub* class itself: it can also be implemented in subclasses. ACMiner therefore uses Soot’s class hierarchy information to identify all of the *stub*’s subclasses. Finally, the class and method information is used to identify all concrete methods in these *stub* and subclasses that match the handler method signatures. These concrete methods become the entry points for analysis.

C THE EXCLUDE LIST

A subset of the exclude list is displayed in Table 4 which groups the excluded elements by the five different procedures we use for excluding elements of the call graph (see our website [1] for the complete exclude list). The first procedure *Class Path* will exclude any method of a class whose full class name either exactly equals the listed name or starts with the listed name when the listed name ends with `*` or `$*`. The second *Interface* excludes any method that implements a method of an interface that exactly equals the listed name. The third *Interface All* excludes all methods of all classes that implement directly or indirectly an interface that exactly equals the listed name. The fourth *Superclass* excludes any method that implements a method of a class that exactly equals the listed name. The fifth *Superclass All* excludes all methods of all classes that extend directly or indirectly a class that exactly equals the listed name. Finally, *Method Signature* excludes a single method that matches the supplied method signature.

To define the exclude list, we explored the call graph, looking for classes and methods that form roots of call graph areas not useful to our analysis. We started by broadly excluding, using the

Table 4: Subset of the Excluded List for the Call Graph

Procedure	Excluded Elements
Class Path	java.*, javax.*, gov.nist.javax.*, org.*, sun.*, com.sun.*, com.ibm.*, com.google.common.*, soot.*, junit.*, com.android.dex.*, dalvik.*, android.test.*, android.text.*, android.util.*, android.animation.*, android.view.animation.*, android.icu.*, android.database.sqlite.*, android.content.res.*, com.android.org.bouncycastle.*, android.graphics.*, android.preference.*, android.os.UserHandle, android.os.Process, android.os.Binder, android.os.Debug, android.net.Uri, android.net.Uri\$, libcore.util.Objects, android.os.Bundle, android.os.Parcel, android.view.View, libcore.io.IOException
Interface	java.lang.Iterable, java.util.Iterator, java.util.ListIterator, java.lang.Comparable, java.util.Comparator, java.util.Collection, java.util.Deque, java.util.Enumeration, java.util.List, java.util.Map, java.util.Map\$Entry, java.util.NavigableMap, java.util.NavigableSet, java.util.Queue, java.util.Set, java.util.SortedMap, java.util.SortedSet, java.lang.Runnable, android.os.Parcelable, android.os.IInterface,
Interface All	java.lang.AutoCloseable, libcore.io.Os, android.database.Cursor
Superclass	java.lang.Object, android.graphics.drawable.Drawable, android.content.Context
Superclass All	com.android.internal.telephony.SmsMessageBase, java.lang.Throwable, android.app.Dialog, android.view.View
Method Signature	DevicePolicyManagerService: void writeToXml(XmlSerializer) UserManagerService: void writeUserLP(UserData) UserManagerService: void writeUserListLP()

Class Path procedure, any packages that are not Android related as these are generic Java libraries and will not contain Android specific authorization checks. Since these generic Java libraries often contain interfaces and classes implemented and extended in code outside the Java libraries, we also found it necessary to use the Interface and Superclass procedures to cover subclasses of these in Android specific code. Next, as we still observed significant bloat, we broadened our search to include Android specific code. We started excluding packages such as `android.icu.*` and `com.android.org.bouncycastle.*` as these are common non-Android libraries that were integrated into the Android specific code but hold no Android-specific authorization checks. Lastly, we looked for methods in the call graph with a large number of outgoing edges and/or a large number of outgoing edges for the same method invoke statement, adding the methods and classes to the exclude list as needed.

In addition to those described above, the exclude list has a few more additions and omissions. First, while `com.android.Context` is excluded using the Superclass procedure, all permission check methods in the class are omitted from this exclusion. This enables ACMiner to capture the authorization checks inside these various important methods. Second, classes such as `android.os.UserHandle` and `android.os.Process` have many authorization check methods, yet are elements of the exclude list. Adding such classes to the exclude list gives context to the operations these authorization-checks perform. Such context would be lost otherwise since the actual checks involve manipulating integers values.

D SIMPLIFICATION OF AUTHORIZATION CHECKS

We apply the following 10 simplification rules when generating authorization checks for an entry point and use the value *ALL* in our output to indicate that a variable can be assigned any value. (1) Any variable that does not represent a variable of a primitive type or a string type is assigned the value *ALL*. We found such variables were safely ignored as they did not add any additional context to the authorization checks being output and instead generated a large amount of noise when included. (2) To handle loops and recursion, a value of *ALL* is assigned if a cycle is detected when resolving the possible values for a variable. (3) When a variable represents a parameter of the current entry point method, a value of *ALL* is assigned as the parameter's value could be anything. (4) A value of *ALL* is assigned to all variables obtaining their value from *lengthof*, *instanceof*, *new*, and *cast* expressions as no new context is gained about the authorization checks by including these expressions. (5) If an expression retrieving a value from an array has the value *ALL* for either its index or its array reference, then a value of *ALL* is assigned to the value retrieved from the array as no new context will be gained from such expressions. (6) Variables assigned from the return of a method in the class *Bundle* always get assigned the value *ALL* since *Bundle* is used to pass data through *Binder* and can therefore be anything. (7) For a control predicates or context queries when computing the product of all the possible variables and the values for each variable, if the possible set of values for a variable contains *ALL* then the set is transformed into a singleton set containing only the value *ALL*. (8) If a variable is assigned a value of *NULL* and has any other value assigned to it, the *NULL* value is ignored so as to remove *NULL* checks. (9) When dealing with the final set of values generated from a control predicate (i.e., a set of pairs), we remove a pair from this set if: the pair has *NULL* or *ALL* for either of its values, the pair has a constant value for both of its values, or both of the values in the pair are equivalent. (10) As Java object *equals* methods when used in a conditional statements take the form `if(o1.equals(o2) == 0)`, the pair generated by *ACMiner* representing the authorization check would normally contain one entry for the value of the *equals* method and one entry for the constant value being compared. However, what is really desired is the values of the objects being compared by the *equals* (e.g., in the case of string comparisons). As such, we simplify the representation of such authorization checks by reconstructing the pairs so that they contain values for the calling object and the argument object (i.e., *o1* and *o2*) of the *equals* method.

E REPRESENTING CONTEXT QUERIES

To generalize our definition of context queries, we developed a representation that allows us to express the context queries as a combination of regular expressions and several string matching procedures used to describe the package, class, and/or method name, combined with conditional logic (i.e., *and*, *or*, and *not*). Table 5 outlines a complete list of the base expressions used to define the regular expressions and string matching procedures. Figure 9 shows an example expression from the set of expressions generated for

Table 5: Method and Field Matching Expressions

Operation	Description
starts-with-(package class name)	Resolves to true if the package, class, or name starts with the given string for some method or field.
ends-with-(package class name)	Resolves to true if the package, class, or name ends with the given string for some method or field.
contains-(package class name)	Resolves to true if the package, class, or name contains the given string for some method or field.
equals-(package class name)	Resolves to true if the package, class, or name equals the given string for some method or field.
regex-(package class name)	Resolves to true if any part of the package, class, or name matches the given regular expression for some method or field.
regex-name-words	Resolves to true if the method or field name matches any part of the given regular expression when the name is split at word boundary indicators.
regex-class-words	Resolves to true if the method or field class matches any part of the given regular expression when the class is split at word boundary indicators. Note this operation takes in a second argument which specifies which class name to match in the case of an inner class. The indexing starts at 0 for the inner most class name and increases by 1 for each outer class name. An index of -1 means the regex can match any of the class names from inner most to outer most.

```
(and
  (or
    (starts-with-package android.)
    (starts-with-package com.android.)
  )
  (regex-name-words `^can\s(clear\sidentity|draw\soverlays
|run\shere|user\smodify\saccounts|access\sapp\swidget
|read\sphone\s(state|number)|caller\saccess\smock)\b`
)
)
```

Figure 9: An example of the expressions used to describe context queries.

Android AOSP 7.1.1 that describes, along with several others, the context query `canClearIdentity` shown in line 19 of Figure 10. In Figure 9 we see the expression is actually made up of 4 different operations. As one would imagine, *and* and *or* operations behave just like their counterparts in normal conditional logic. Furthermore, *starts-with-package* behaves as expected in that it checks to see if the package name of the class in which a method is defined starts with a given string, in this case either `android.` or `com.android.`. Finally, *regex-name-words* is a bit more complicated in that checks to see if any part of a method name matches the given regular expression when the method name is split by word boundary indicators (i.e., splitting the name at capital letters in the case of camel-case or at an underscore character). That is, for the method named `canClearIdentity`, the method name is transformed into the string `can clear identity` before the regular expression matching is performed. By splitting the method name at word boundary indicators, this allows the regular expressions to be defined in terms of key words without having to worry about situations where one word might contain

¹http://androidxref.com/7.1.1_r6/xref/frameworks/base/services/core/java/com/android/server/am/ActivityManagerService.java#11401

```

1 public String getProviderMimeType(Uri uri, int userId) {
2     enforceNotIsolatedCaller();
3     int callingUid = Binder.getCallingUid();
4     int callingPid = Binder.getCallingPid();
5     boolean clearedIdentity = false;
6     long ident = 0;
7     if (canClearIdentity(callingPid, callingUid, userId)) {
8         clearedIdentity = true;
9         ident = Binder.clearCallingIdentity();
10    }
11    ...
12 }
13
14 void enforceNotIsolatedCaller(String caller) {
15     if (UserHandle.isIsolated(Binder.getCallingUid()))
16         throw new SecurityException();
17 }
18
19 boolean canClearIdentity(int pid, int uid, int userId) {
20     if (UserHandle.getUserId(uid) == userId)
21         return true;
22     if (checkComponentPermission(INTERACT_ACROSS_USERS, pid,
23         uid, -1, true) == 0
24         || checkComponentPermission(INTERACT_ACROSS_USERS_FULL, pid,
25         uid, -1, true) == 0)
26         return true;
27     return false;
28 }

```

Figure 10: Pseudo-code from the ActivityManagerService class.¹

others in its spelling (e.g., *is* and *list*).

F DEFINING CONTROL PREDICATES FILTER

The first step in defining the control predicate filter was to have a domain expert explore the unique fields, strings, and methods (i.e., elements) used in every marked conditional statement to decide which of these elements are used in an authorization context and which are unimportant. In general, the exploration of these lists proceeds as follows: (1) Start by looking at the control predicates contained within context queries and the name of the context queries themselves. As any element used within control predicates of context queries are likely important, we can already include these elements in our list of elements that indicate control predicates. However, by studying the control predicates, we can also gain further insight into what control predicates might look like elsewhere in Android’s code. Moreover, we can learn key words that might help with identifying additional elements with authorization context from our lists. (2) Perform a search on our lists of elements using the key words learned from the previous step as these can indicate common functionality. (3) Verify if the elements resulting from the previous search are actually used in control predicates by looking at both how all conditional statements use an element and the overall flow of the methods containing the conditional statements using the element. Add any that are determined to be used in control predicates to our list of elements that indicate control predicates. Note, when recording elements that indicate control predicates it is also important to indicate exactly how the elements are being used in control predicates as certain elements may only be authorization related in specific context. For example, as shown in Figure 13, some control predicates involve the use of methods that only when combined together in a specific way construct an authorization check (e.g., the string equals method and the get method of SystemProperties when get is provided the string SYSTEM_DEBUGGABLE). (4) On the remaining unchecked elements, go through each element as in step 3. If new key words are added to our key word list as a result of finding a new indicator element,

```

<KeepFieldValueUse Value="(and
(regex-name-words `b(flag(s)?)\b`)
(regex-class-words `b((uri\spermission)
|((package|application)\smanager\smanager\smanager)
|permission\s(state|data)|package\ssetting
|layout\sparams|display|(activity|application)
|provider|user|service|display|device)\sinfo)\b` 0)
)">
<Restrictions UseUnion="false">
<IsInArithmeticChain HandleConstants="false"/>
</Restrictions>
</KeepFieldValueUse>

```

Figure 11: An example of the an entry in the control predicate filter. This entry matches a number of flag field control predicates, such as Figure 13 line 6, by their name, class, and use that have authorization context.

perform steps 2-3 again. Keep performing step 4 until all elements in our lists have been processed.

In defining the control predicate filter, it is important to understand that the use of the fields, methods, and strings identified do not always indicate control predicates. Instead, they indicate control predicates when used in a specific context. As such, any filter we design will have to allow us to specify such a context along with the fields, methods, and strings. Therefore, while we cannot rely solely on the expressions outlined in Table 5 we can reuse them. We use a customized XML document that ACMiner takes in as input as shown in Figure 3 as our filter specification. The filter specification is constructed from a group of rules that are conditionally joined together using the *and*, *or*, and *not* operators into one large conditional expression that specifies if a given conditional statement should be included in our final list of control predicates.

Figure 11 provides an example rule from our filter specification. It details the rule *KeepFieldValueUse* used to match the control predicate at line 6 of Figure 13. As shown, the rule uses the expressions outlined in Table 5 to first identify the use of a flag field in a conditional statement that may potentially indicate a control predicate. The rule then further restricts what is considered a control predicate by applying the restriction *IsInArithmeticChain*. This restriction only allows conditional statements to be considered control predicates if the field or method return value is used in a chain of arithmetic expressions whose resolution is then used in the conditional statement. The arithmetic operations are all standard Java binary and unary operators (e.g., +, -, ==, !=, and !). Such a restriction allows us to exclude situations like `if(0 == method(flag))` where the flag field is being used in a conditional statement as an argument to a method while including conditional statements who use field and method return values as in Figure 13 line 6.

To further illustrate how rules are expressed in our filter specification, we take a look at the more complex example of Figure 12 which is a rule to match control predicates like line 5 of Figure 13. The rule *KeepMethodReturnValueUse* specification is similar to that of *KeepFieldValueUse* from our previous example except it has an additional set of restrictions. These restrictions are all forms of the *IsValueUsedInMethodCall* which enables us to specify the possible arguments for a method as well as the possible calling object of the method. In this case, we have two sets of nested *IsValueUsedInMethodCall* restrictions the results of which are ored together when evaluated. The outer most *IsValueUsedInMethodCall* restriction in either set specifies that only the methods whose return value is

```

<KeepMethodReturnValueUse Value="(equal-name equals)">
  <Restrictions UseUnion="false">
    <IsInArithmeticChain HandleConstants="false"/>
    <Restrictions UseUnion="true">
      <IsValueUsedInMethodCall Position="-1">
        <Matcher class="MethodMatcher" Value="(and
(regex-class-words '\\system\\sproperties\\b` 0)
(regex-name-words '\\bget\\b`)'
)"/>
      <Restrictions UseUnion="false">
        <IsValueUsedInMethodCall Position="0">
          <Matcher class="StringMatcher" Value="(
regex `ro\\. (factorytest|test_harness
|debuggable|secure)`
)"/>
        </IsValueUsedInMethodCall>
      </Restrictions>
    </IsValueUsedInMethodCall>
    <IsValueUsedInMethodCall Position="0">
      ...
      // Same data as
      // <IsValueUsedInMethodCall Position="-1">
      // except flipped
    </IsValueUsedInMethodCall>
  </Restrictions>
</KeepMethodReturnValueUse>

```

Figure 12: An example of the an entry in the control predicate filter. This entry specifically matches situations such as the control predicate shown in Figure 13 line 5.

used as part of the equals call, whose name contains get, and who is a member of the class SystemProperties be considered a control predicate. The *Position* attribute of *IsValueUsedInMethodCall* specifies where this restriction is to check for a value matching this description (i.e., -1 for the calling object and 0 for the first argument of the method). The inner *IsValueUsedInMethodCall* restriction of each set then further specifies that any method matching the outer restrictions description must also take as an argument at position 0 a string that matches the given regex. Combining all these restrictions together, we get a rule that says to treat any conditional statements as *cps* if they are checking if a value *A* equals some string where *A* is the return value of a get method in SystemProperties retrieving the associated system value for some given key.

Aside from rules like those presented above, the filter also covers a few corner cases. Mainly context queries and loop conditionals. As defined in Section 4.1.2, any conditional statement in a context query or using a context query’s return value should be considered a control predicate. As such, the filter should always include these conditional statements as control predicates. The filter uses the description of context queries (see Section 4.2.1) to identify context queries and preserve conditional statements as control predicates if a conditional statement is within the body of a context query or the context query’s return value is used in an chain of arithmetic expressions. Moreover, as mentioned above, one of the main sources of noise in ACMiner’s view of the authorization checks was loop conditionals (i.e., the conditional statements that decide if the control flow should exit a loop). As loops conditionals are not important when viewing Android’s authorization checks the filter explicitly rejects all conditional statements that are loop conditionals.

²http://androidxref.com/7.1.1_r6/xref/frameworks/base/services/core/java/com/android/server/ma/ActivityManagerService.java#21497

```

1 public boolean dumpHeap(String process, int userId, ...) {
2     if(checkCallingPermission(SET_ACTIVITY_WATCHER) != 0)
3         throw new SecurityException();
4     ProcessRecord proc = findProcess(process, userId);
5     if (!("1".equals(SystemProperties.get(SYSTEM_DEBUGGABLE, "0")))
6         && 0 == (proc.info.flags & ApplicationInfo.FLAG_DEBUGGABLE))
7         throw new SecurityException();
8     ...
9     return true;
10 }
11
12 ProcessRecord findProcess(String process, int userId) {
13     int pid = Binder.getCallingPid();
14     int uid = Binder.getCallingUid();
15     userId = handleIncomingUser(pid, uid, userId, true,
16         ALLOW_FULL_ONLY, null);
17     ...
18     return proc;
19 }
20
21 int checkCallingPermission(String permission) {
22     int pid = Binder.getCallingPid();
23     int uid = UserHandle.getAppId(Binder.getCallingUid());
24     return checkComponentPermission(permission, pid, uid,
25         -1, true);
26 }
27
28 int checkComponentPermission(String permission, int pid, int uid,
29     int owningUid, boolean exported) {
30     if(pid == MY_PID)
31         return 0;
32     int appId = UserHandle.getAppId(uid);
33     if(appId == 0 || appId == 1000
34         || UserHandle.isIsolated(uid)
35         || (owningUid >= 0 && UserHandle.isSameApp(uid, owningUid)))
36         return 0;
37     if (!exported)
38         return 1;
39     return checkUidPermission(permission, uid);
40 }

```

Figure 13: Pseudo-code from the ActivityManagerService class.²

G COMPLETENESS PROOF FOR CLOSED ASSOCIATION RULE MINING

LEMMA G.1. *If $X \implies Y$ is a closed association rule and not confident (i.e., $\text{conf}(X \implies Y) < \text{minconf}$), there does not exist an itemset $Y' \subset Y$ where $X \implies Y'$ is a confident association rule (i.e., $\text{conf}(X \implies Y') \geq \text{minconf}$) unless $X \cup Y'$ is also a closed frequent itemset.*

PROOF. Let $\text{conf}(X \cup Y) = \frac{\sigma(X \cup Y)}{\sigma(X)}$ and $\text{conf}(X \cup Y') = \frac{\sigma(X \cup Y')}{\sigma(X)}$ where $Y' \subset Y$. If $\text{conf}(X \implies Y') \geq \text{conf}(X \implies Y)$, then $\sigma(X \cup Y') \geq \sigma(X \cup Y)$. Due to the monotonicity property, $\sigma(X \cup Y') \geq \sigma(X \cup Y)$, because $Y' \subset Y$ and $\sigma(Y') \geq \sigma(Y)$. If $\sigma(X \cup Y') = \sigma(X \cup Y)$, then $\text{conf}(X \cup Y') < \text{minconf}$. If $\sigma(X \cup Y') > \sigma(X \cup Y)$, then $X \cup Y'$ is also a closed itemset according to Lemma G.2. \square

LEMMA G.2. *If $X \cup Y$ is a frequent closed itemset, then $X \cup Y'$ where $Y' \subset Y$ is also a frequent closed itemset if $\sigma(X \cup Y') > \sigma(X \cup Y)$.*

PROOF. Let $\sigma(X \cup Y') > \sigma(X \cup Y)$ and $\alpha(X \cup Y) \neq \emptyset$. For $X \cup Y'$ to not be a frequent closed itemset, then $\exists Y'' \supset Y' \mid \sigma(X \cup Y'') = \sigma(X \cup Y')$ by the definition of a frequent closed itemset. If $\sigma(X \cup Y'') = \sigma(X \cup Y')$, then $\alpha(X \cup Y'') = \alpha(X \cup Y')$. Further, since $\sigma(X \cup Y') > \sigma(X \cup Y) \wedge \alpha(Y) \neq \emptyset$, then $\alpha(Y) \subset \alpha(Y'')$. If $\alpha(Y) \not\subset \alpha(Y'')$, then $\sigma(X \cup Y'') < \sigma(X \cup Y')$ by definition. Since $Y \supset Y'$ exists and $\sigma(X \cup Y'') = \sigma(X \cup Y')$, then $\sigma(X \cup Y \cup Y'') = \min(\sigma(X \cup Y), \sigma(X \cup Y''))$ by the monotonicity property. Since $\sigma(X \cup Y') > \sigma(X \cup Y) \wedge \sigma(X \cup Y'') = \sigma(X \cup Y'') \implies \sigma(X \cup Y \cup Y'') = \sigma(X \cup Y)$. Therefore, $\nexists X \cup Y'' \mid \sigma(X \cup Y'') = \sigma(X \cup Y')$, because $X \cup Y$ is defined as a closed itemset. Thus, $X \cup Y'$ is also a frequent

closed itemset. □

H NON-SECURITY INCONSISTENCIES

ACMiner identified 423 inconsistencies (i.e., rules) that did not represent vulnerabilities. Aside from the 20 rules that were caused by easily fixed bugs in ACMiner, we resolve these non-security inconsistencies to their likely causes, and classify them into 9 categories, shown in Table 3 (RQ3).

H.1 Irregular Coding Practices

In addition to detecting vulnerabilities, ACMiner can also be useful for detecting irregular coding practices in Android’s system services. This may not only improve code quality, but may also help increase computation speed, fix access bugs, or indicate locations of future vulnerabilities, as described below.

1. Shortcuts to Speed-Up Access: As Table 3 shows, ACMiner detected 7 inconsistencies that when fixed will improve the performance of the system. For example, consider the `BatteryStatsService`. In this service, whenever an entry point checks for the permission `UPDATE_DEVICE_STATS`, the entry point first calls `enforceCallingPermission`, which contains an additional `PID` check that grants the service quick access to its own entry point, bypassing the permission check. This optimization speeds up access without a significant security-cost. Now consider another entry point `takeUidSnapshots` in the same service. ACMiner recommended this same `PID` check to be included when other permissions in the service `BATTERY_STATS` permission is checked for this entry point, i.e., ensuring the consistent application of such valuable short cuts.

2. Fixing Access Bugs: ACMiner detected 2 inconsistencies that when fixed solve access-related bugs, i.e., discrepancies in how a permission should be used (i.e., as per the documentation). For example, consider the entry point `getUserCreationTime` of the `UserManagerService`. The entry point is currently limited to being called by either the same user as the user indicated by the `userId` passed in as an argument or a parent of user. However, other similar entry points in the service also grant access to callers with the *signature* level permission `MANAGE_USERS`. Thus, ACMiner recommends the addition of the `MANAGE_USERS` permission check to this entry point. This is consistent with the documentation, which states that callers with the `MANAGE_USERS` permission may call `getUserCreationTime`.

3. Potential Vulnerabilities: ACMiner detected 16 inconsistencies which may lead to future vulnerabilities. Consider the entry point `deletePackage` in the `PackageManagerService`, which checks for the permission `INTERACT_ACROSS_USERS_FULL` when verifying if the calling user can operate on the user represented by the `userId` argument. Almost all the entry points in the service use the authorization check `enforceCrossUserPermission` to perform a similar user-related authorization check. That is, `deletePackage` still performs the hard-coded permission check, and is inconsistent with the majority that call the modular `enforceCrossUserPermission` permission check. Thus, there is as strong possibility that the hard-coded check in `deletePackage` may be overlooked when additional user-related enforcement is introduced, resulting in a vulnerability.

H.2 Improvements to ACMiner’s Accuracy

Our systematic investigation of ACMiner’s results leads to 6 causes of non-security rules that motivate future work:

1. Difference in Functionality: A majority of the non-security inconsistencies (i.e., 189) were caused in cases where the target and supporting entry points contained unrelated protected operations, and thus, comparing their authorization checks resulted in unusable association rules. We are exploring techniques such as call graph comparison and method-name comparison to improve entry point groupings to mitigate such rules.

2. Checks With Different Arguments: We observed 66 non-security inconsistencies where same authorization checks were instantiated in code with slightly different arguments, without affecting the security context. This problem may be mitigated by making ACMiner’s analysis more precise, i.e., by analyzing consistency in terms of the relevant arguments and variables that actually affect the security context of the authorization check. Such fine-grained analysis is a non-trivial problem for future work.

3. Noise in Captured Checks: Despite the use of the control predicate filter, ACMiner still identifies some conditional statements and method calls improperly as authorization checks. We have already determined the statements causing this issue, and are addressing it via a routine refinement of the control predicate filter as well as the expressions used to identify context queries.

4. Restricted to Special Callers: We found that numerous entry points in the system are restricted to being called by special callers (e.g., the `UID` of system, shell, or root). As a result, any association rules generated for such entry points are valueless since the target entry point is more restrictive than the supporting entry points. We are exploring the integration of a unified view of the hierarchy among the different authorization checks in ACMiner (i.e., in terms of which checks supersede others) to mitigate such issues.

5. Semantic Groups of Checks: We observed that a number of unrelated permission checks are always accompanied by checks for the system or root `UID` or isolated processes. Thus, ACMiner ends up generating rules using the `UIDs/isolated process` checks as supporting authorization checks, recommending unrelated permissions as the missing authorization checks. That is, since ACMiner does not consider such semantic groups, it generates multiple incorrect rules in cases where a few entry points check for different, unrelated, permissions, while also checking for `UIDs/isolated processes`. From our analysis of the results, we have discovered that such rules can be filtered out as the generally follow a pattern.

6. Equivalent Checks: ACMiner does not consider the semantic equivalence between authorization checks, and thus, cannot eliminate association rules generated due to multiple checks having the same outcome. Fortunately, we have discovered numerous sets of equivalent checks through this analysis, which we plan to apply to ACMiner to improve its accuracy.