A Large Scale Investigation of Obfuscation Use in Google Play

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ABSTRACT

Android applications are frequently plagiarized or maliciously repackaged, and software obfuscation is a popular protection against these practices. In this study, we present the first comprehensive analysis of the use and challenges of software obfuscation in Android applications. We surveyed 308 Google Play developers about their experiences with obfuscation, finding that the free ProGuard software is by far the most commonly used obfuscation tool. With this insight, we analyzed 1.7 million Android apps from Google Play, finding that only 24.9% of apps are obfuscated by the primary developer. This is surprising, given that the most common integrated development environment for Android, Android Studio, includes ProGuard by default. We investigated root causes of this low rate of obfuscation in an in-depth study with 79 Google Play developers, assessing their experiences with obfuscation and asking them to obfuscate a sample app using ProGuard.

We found that while developers feel that apps in general are at risk of malicious repackaging or plagiarism, they do not fear theft of their own intellectual property. Developers also report difficulties applying obfuscation for their own apps, which was substantiated when they demonstrated problems with all but the most basic configurations to obfuscate our sample app. Our findings indicate that more work is needed to make the application of obfuscation more usable and to educate developers on the risk of their apps being reverse engineered, their intellectual property stolen and their apps being repackaged and redistributed as malware.

KEYWORDS

Obfuscation, Android, User Study

1 INTRODUCTION

Android is the world's leading mobile platform, with an estimated 327.000 shipped units and 87.7% market share in Q4 2017 [47], it is also the top choice of mobile developers surveyed [46], and consequently the Google Play market features over 3 million apps [2]. These apps face significant risks from reverse engineering [15] because app plagiarism is a common phenomenon in the Android ecosystem. Some plagiarists repackage applications with new advertising library identifiers so that the plagiarist can steal ad revenue [24], while other plagiarists create Trojan horse malware [52, 58, 59]. Not only does this directly or indirectly harm the developers (by stealing revenue or harming reputation), but having to distinguish original applications from their repackaged, often malicious counterparts places unnecessary burden on the average Android user [16]. While preventing repackaging into malware is of strong

interest for single developers, it is even more important for the entire Android ecosystem as a whole. The harder it is for cyber-criminals to turn benign apps into malware or to steal advertising revenue, the healthier the ecosystem will be.

To address the problems of software plagiarism, malicious reverse engineering, and repackaging, developers rely primarily on software obfuscation [8, 9, 11, 51]. While on other platforms obfuscation relies on niche or ad-hoc tools, it is nominally a first-class citizen in Android. The officially supported development platform, Android Studio [25], includes the ProGuard tool [33] capable of obfuscation by default.

Although obfuscation should be a crucial first line of defense against malicious reverse engineering and repackaging, it is unclear to what extent it is actually used in benign Android applications, nor to what extent Android developers understand the concept of obfuscation, what their mental models are, and whether currently existing obfuscation tools for Android are sufficiently easy-to-use to be widely employed.

In this paper, we present the first examination of the state of obfuscation practices in the Android ecosystem by conducting user studies with hundreds of Google Play developers and analyzing 1.7 million Google Play applications. Our comprehensive analysis shows that while developers are aware of the benefits of obfuscating their apps on a theoretical level, a perceived negligible personal impact and the time-consuming use of ProGuard in real world applications is a large deterrent to using obfuscation.

Overall, our paper makes the following contributions:

- Developer survey: We present results of an online survey with 308
 Google Play developers regarding their obfuscation background,
 tool usage, and perception. We find that while developers are
 generally aware of obfuscation and the threats associated with
 reverse engineering, they perceive the risks to their own apps
 as low and consider obfuscation to be an unnecessary effort.
- Measurement of obfuscation in Google Play applications: We developed Obfuscan to evaluate the use of ProGuard and similar obfuscation tools in 1.7 million free Google Play applications. We find that while many libraries are obfuscated, approximately 75% of developers do not obfuscate their own code. We also find that while apps with high download counts are generally more likely to be obfuscated, only half of the apps with over 100 million downloads use obfuscation.
- Obfuscation Study: We investigate challenges when using Pro-Guard in a programming study with 79 Google Play developers by asking our participants to complete multiple obfuscation

tasks using ProGuard. While most developers successfully managed to complete a simple obfuscation task, they failed to correctly use ProGuard in a more complex and realistic scenario.

We acknowledge that software obfuscation is not a "silver bullet" that defends against all reverse engineering, but previous work shows that even simple forms of obfuscation (like identifier renaming) significantly increase the effort required to successfully reverse engineer software [8, 9]. Thus, software obfuscation is an effective and worthwhile practice to be encouraged. Moreover, it is critical to understand what prevents developers from obfuscating their applications.

2 RELATED WORK

We discuss related work in three key areas: research into the benefits of software obfuscation; attempts at developing obfuscationresistant Android analysis software; and developer studies performed for the Android platform.

Software obfuscation. Software obfuscation has been studied in many contexts, including as defense against reverse engineering [12], to prevent intellectual property attacks [13], as disguise for malware [54], and to avoid user profiling [49]. Researchers successfully employed code obfuscation techniques to avoid detection tools, including anti-malware software [40, 41, 56], repackaging detection algorithms [30], and app analysis tools [28], although performance of anti-malware software improved in a more recent study [37]. A number of works detail different obfuscation techniques in general [7, 11, 12, 54], and for the Java programming language in particular [10, 29, 43]. On the Android platform, Ghosh et al. discussed a number of obfuscation techniques that increase the complexity of the control flow to counter reverse engineering [23]. Similarly, Jung et al. investigated vulnerabilities of Korean banking apps against repackaging and suggested code obfuscation as one of multiple counter-measures [32]. Others have investigated the capabilities of software obfuscation for the hiding of Android malware: Protsenko et al. and Faruki et al. developed obfuscation frameworks for Dalvik bytecode and revealed shortcomings in popular anti-malware products [19, 40].

Obfuscation-resistant Android analysis software. We investigate obfuscation in the Android ecosystem with a developed detection tool, Obfuscan. The wide range of available Android security analysis software [42] includes a number of detection tools that are resistant against obfuscation. These tools focus on the detection of code reuse [27, 55], the detection of repacked malware [20, 22, 35, 45], or identification of third-party libraries [3, 36]. Compared to Obfus-CAN which detects and measures actual obfuscation features, these tools focus on the detection of functionally similar or suspicious structures despite obfuscation. Linares-Vásquez et al. revisited Android reuse studies in the context of third-party library usage and code obfuscation [34]. With a simple heuristic of detecting the presence of a.java classes in main packages, they identified 415 obfuscated apps in a dataset of 24,379 randomly sampled apps from Google Play and suggested that code reuse studies should account for the impact of obfuscation and third-party libraries. Compared to this simple binary classification over few applications, Obfuscan detects a complete set of obfuscation techniques for a large-scale

dataset of 1.7 million apps. A step further than detection is the reversal of obfuscation by deobfuscation [48]. The DeGuard tool developed by Bichsel et al. reverses ProGuard obfuscation with probabilistic learning [6]. While earlier work relating to obfuscation in Android apps focused on either reversing the effects of obfuscation or on detecting certain features of an app despite obfuscation, we detect multiple obfuscation features in a large-scale dataset and perform a root cause analysis with Google Play developers to place results in a better context.

Android developer studies. Previous Android developer studies were performed in the context of privacy, Trusted Layer Security/Secure Sockets Layer (TLS/SSL) security, and cryptographic Application Programming Interfaces (APIs). Balebako et al. performed interviews and online surveys to investigate how app developers make decisions about privacy and security, identifying several hurdles and suggesting improvements that would help user-privacy [4, 5]. Jain et al. suggested design changes to the Android Location API based on the results of a developer lab study [31]. Fahl et al. and Oltrogge et al. conducted developer surveys and interviews, revealing deficits in the handling of TLS/SSL and suggesting several improvements [17, 18, 39]. Nadi et al. found in a study that Java developers struggle with perceived low-level cryptography APIs [38]. Concerning obfuscation on the Android platform, Ceccato et al. assessed in experiments the impact of Java code obfuscation on the code comprehension of students, finding that obfuscation delays, but not prevents tampering [8, 9]. Compared to these works, our root cause analysis focuses on obfuscation knowledge and ability to use the obfuscation tool ProGuard among Google Play developers. Related to a previous developer study investigating the impact of information sources on code security by Acar et al. [1], we find that developers are generally knowledgeable about the benefits and basic configuration, but fail to correctly perform the process for more complex setups.

3 ANDROID OBFUSCATION BACKGROUND

Obfuscation tools for the Android ecosystem cover a wide range of price tiers and feature categories. Available tools range from free, open-source obfuscation solutions providing only basic obfuscation features such as ProGuard, up to premium obfuscation environments with high monthly per-developer-licensing fees such as DexGuard (cf. Table 1).

The free ProGuard enjoys preferential treatment in the Android ecosystem. It is included with the Android SDK and supported by the official Android Studio IDE. In addition, other obfuscation tools inherit most of their obfuscation functionality from ProGuard; the now deprecated alternative tool chain Jack is configured by ProGuard configuration files and provides ProGuard's obfuscation with reduced options. Similarly, Redex accepts ProGuard's configuration files and mirrors the renaming functionality closely. DexGuard, ProGuard's commercial extension, utilizes name obfuscation with the same basic functionality as ProGuard, but with extended features and symbol space. Due to these similarities, Obfuscated with ProGuard but also with other tools listed in Table 1.

| | | Obfuscation | Other | |
|-------------------------|------------|---|---|--|
| Name | License | Package name Class name Method name Field name Overloading Debug Data Annotations | String Enc. Class Enc. Optimization Minimization Watermarking | |
| Allatori ^{1,†} | \$290 | • • • • • • | • • • • | |
| APKProtect | Free | Not maintained s | ince 2013 | |
| DashO [†] | On request | • • • • • • | \bullet \circ \bullet \circ \bullet | |
| DexGuard ^{2,†} | On request | • • • • • • | \bullet \bullet \bullet \circ | |
| DexProtector | \$800 | \bullet \bullet \bullet \circ \circ \circ | \bullet \bullet \circ \circ | |
| GuardIT | On request | \bullet \bullet \bullet \bullet \bullet | \bullet \bullet \circ \circ \circ | |
| Jack ^{3,†} | Free | $\bullet \bullet \bullet \bullet \circ \bullet \bullet$ | $\circ \circ \bullet \bullet \circ$ | |
| ProGuard ^{4,†} | Free | • • • • • • | $\circ \circ \bullet \bullet \circ$ | |
| ReDex ^{5,†} | Free | • • • • • • | $\circ \circ \bullet \bullet \circ$ | |
| yGuard † | Free | • • • • • • | 00000 | |

- ¹ Multiple obfuscation patterns, default can be detected
- ² Extends ProGuard's features, subset can be detected
- ³ Subset of ProGuard's features with same configuration format, deprecated
- $^4\,$ Included with official Android SDK and integrated with Android Studio
- Mirrors ProGuard's obfuscation with same configuration format
- † Obfuscation features (partially) detected by Obfuscan

Table 1: Selected features of popular obfuscation software for the Android environment.

In addition to the fact that many tools are related to ProGuard, Obfuscan also detects features that would be used by any obfuscation tool including other name obfuscation patterns (e.g., replacing class names with restricted keywords of the Windows operating system by DexGuard or Allatori), removal of certain field meta data (e.g., debug information or annotations), or modifications to packaged files (e.g., renaming the classes.dex file). Hence, while being specifically developed to detect ProGuard-based obfuscation, Obfuscan can be used to detect any kind of name obfuscation in Android applications. While more advanced obfuscation techniques such as string encryption are not detectable using Obfuscan, it can be used to find out whether an Android application uses obfuscation at all.

3.1 Why Software Obfuscation Matters

Obfuscation provides a defense against several undesired activities. First, it protects design secrets from being made public. In situations where algorithms or trade secrets are embedded in application code, obfuscation makes these secrets more difficult to acquire. This may be important in some domains (e.g., apps that embed custom machine learning models) but not in others (e.g., wallpapers). More importantly, software obfuscation prevents code theft and reuse. Many developers (including our survey participants) primarily think of this problem as one of a legitimate competitor stealing portions of code to simplify their own development. This is a rare and unlikely practice. A far less rare practice is wholesale app theft — known as repackaging — where an adversary copies the entire app; this can be done to insert malicious code. Another common behavior is to profit from an existing app's popularity

by repackaging it with different advertising libraries that pay the adversary and releasing the app onto third party markets (perhaps at a lower price). [21]

The practice of repackaging is epidemic, and represents a threat to the entire ecosystem. Zhou et al. found that 86% of malware samples they collected were repackaged versions of benign applications [59], and in a related project found that up to 13% of entire third party markets consist of plagiarized, repackaged apps [57, 58]. Other measurements have shown that apps are repackaged by the thousands [14, 50], and in fact one of our participants was a victim of app repackaging on multiple occasions. The consequence of this is that end users are regularly threatened by malicious code, and app developers risk losing revenue that is being stolen by adversaries in advertising fraud. Moreover, by infecting devices or cheating developers the practice of app repackaging threatens the popularity of the platform for both end users and developers alike.

Software obfuscation provides a practical solution to this problem, and while not perfect, does provide some benefits in an otherwise difficult situation. Other approaches to code protection – like secure computation or using secure enclaves - are simply impractical for Android developers. For example, provably secure mechanisms (e.g., secure computation) are computationally expensive and are designed for "pure computations" (e.g, set intersection) - not for mundane system challenges like writing click wrappers for UI buttons. As another example, mechanisms that hide leverage secure enclaves are not available to end developers on the Android platform. Software obfuscation is sometimes derided as "security by obscurity." Such "security by obscurity" is regularly lampooned by practicing security professionals, usually for good reason: obscurity is often used by novices in the place of actually effective protections. However, in some cases, obscurity can help security, especially when there are no other effective and/or practical security mechanisms. This is certainly the case when protecting code to run on a client device.

One of our study participants included an analogy to describes his or her approach to obfuscation:

"A bear jumps out of a bush and starts chasing two hikers. They both start running for their lives, but then one of them stops to put on his running shoes. His friends says, 'What are you doing? You can't outrun a bear!' His friend replies, 'I don't have to outrun the bear; I only have to outrun you!"

We feel this analogy summarizes the perceived benefits of obfuscation nicely: while one might argue about the efficiency of preventing code analysis via obfuscation, it does provide a difficulty layer for malicious repackaging and software piracy, as well as a side benefit of optimization that our participants occasionally mentioned.

We note that the benefits of obfuscation certainly depend on the efficacy of the obfuscation applied. In this paper, we focus on ProGuard ¹. Though ProGuard is not as technically sophisticated as other tools, we find that it is the most commonly used tool in Android applications. We expect this is due to the fact that ProGuard is freely available to developers and built in to Android

¹Though not to the exclusion of other obfuscations tools.

Studio. We find that only 0.22% of apps use what is likely a non-ProGuard-related obfuscation tool. To the best of our knowledge, there is much anecdotal evidence about the effectiveness of various obfuscations, but little rigorous empirical evidence of this. In a recent survey, Schrittwieser et al. found that simple obfuscation techniques can still be effective against automated analyses [44]. However, they also note that metrics for effectiveness of obfuscation are still elusive, despite the popularity of software obfuscation. Another suite of studies investigated the effects of obfuscation on the ability of reverse engineers to efficiently or correctly analyze Java code after obfuscation was applied [8, 9]. In that work, Ceccato et al. found that on average obfuscation reduced the efficiency of reverse engineers by a factor of between two and four. Apart from this study, there is a mountain of anecdotal evidence from practitioners in industry. The authors of this paper (who have extensive experience reverse engineering Android applications) have found that ProGuard obfuscation doubles the amount of required analysis time for an exhaustive security audit. Other pieces of anecdotal data include the the problems that malware analysts face when dealing with malware packers.

We note that while the question is beyond the scope of this work, more evidence is needed to characterize the effectiveness of software obfuscation, especially for mobile applications, as well as the effectiveness of obfuscation on preventing repackaging. As this paper is the first step in analyzing obfuscation of *legitimate* software in the Android ecosystem, we hope that the techniques we develop in this work will facilitate such analyses in future work.

4 DEVELOPER SURVEY

We performed an online survey with Google Play developers to investigate their obfuscation practices²: we asked them whether they had heard of obfuscation, whether they knew what it was, whether they had ever used it or decided against using it, and why. Additionally, we measured their awareness of "repackaging", "reverse engineering", "software plagiarism", and "obfuscation". We asked how strongly they feel that apps in general and their own apps in particular are threatened by the first three concepts. We followed this up with a set of general questions about their Android development practices.

4.1 Results

Of the 308 valid participants in this survey, 241 (78%) had heard of obfuscation. 187 (61% of valid participants, 78% of those who had heard of obfuscation) had thought about obfuscating their apps. 148 (48%) had obfuscated one or more apps in the past. 210 (68%) participants had heard of obfuscation in the context of Android, while 253 (82%) had heard of reverse engineering, 201 (65%) of software plagiarism and, 189 (61%) of software repackaging. They felt that apps in general were most threatened by reverse engineering, but felt that their own app was less likely to face those threats than apps "in general" (cf. Figure 1).

One participant explicitly stated "I wasn't sure my apps would be even popular enough so that someone would bother to copy them. If they would get popular, I'd release an update with obfuscation on."

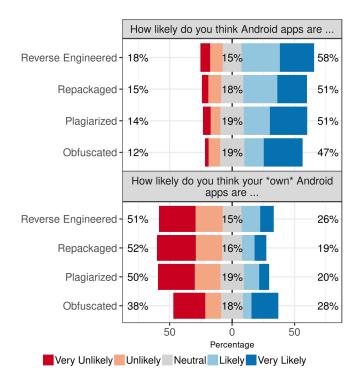


Figure 1: Answer distribution of the online questionnaire as Likert plots. "Don't know" answers are omitted.

Another said "I see it as highly unlikely, that someone is actually interested in reverse engineering my code. I have encountered several fraud cases as an Android developer. All consisted of minimum reverse engineering efforts, i.e. people decompiled my app, changes the advertising ID code, repacked it, and published it under a different name."

A third answered "2.2 millions [sic] of apps in Google Play. who would decompile my app?"

Of the 148 developers who said they already used obfuscation, only 79 verified that obfuscation was successful; however, some assumed successful obfuscation "when no compile error appeared anymore" or "the app worked". 127 of them stated they had prior experience with ProGuard, while 87 Developers stated they actively decided against using it. This implies a high rate of people who tried ProGuard but gave up on actually using it, which is confirmed by some of the comments discussed later on. Risk perception of theft of intellectual property is low — only 102 (33%) developers were afraid of this.

One developer said that obfuscation was "just another step for me. Decided risk is not perhaps great enough to justify the extra work"

Someone else mentioned that "It's time consuming. Often it will break something and I don't think I'm such a high value target that people will repackage my app."

Several developers mentioned that obfuscation was "too much trouble" or "too much effort".

We analyzed three free text questions asking developers for reasons that motivated them to use obfuscation, why developers

 $^{^2 \}mathrm{Full}$ question naire included in appendix

who knew about obfuscation did not use it and how they verified that obfuscation was working as expected. Two researchers coded answers independently. Conflicts were resolved with the help of a third researcher.

Reasons to obfuscate: The majority of developers (58.4%) stated they used obfuscation to protect their intellectual property against malicious reverse engineering. However, 13.2% of the developers said they used ProGuard's obfuscation features because it came with Android Studio for free and was so easy to use. 16.8% used obfuscation because they wanted ProGuard's optimization features and adding obfuscation was trivial. 4% suffered from a misconception of what obfuscation can do. They turned it on to give their users some extra level of security similar to encrypting files or using secure network connections. 6.2% turned on obfuscation because there was a policy (either given by the company they worked for or a customer) that dictated its use.

Reasons to not obfuscate: Most developers (54.8%) who thought about obfuscation and then decided against using it did not feel they had to protect their applications against reverse engineering, either because they open sourced their applications or included no valuable intellectual property. 35% of the developers stated they tried to use obfuscation and gave up since it was too complicated. They could not get third party libraries to run or had other issues such as non-working JavaScript interfaces. 5.8% of the developers said there was a company policy that did not allow them to obfuscate code. However, no one elaborated on those policies in more detail. 3.2% said they tried to understand the concept of obfuscation and gave up when they could not see how obfuscation could provide any protection against reverse engineering and plagiarism.

Verifying that obfuscation works: 75% of the developers who said they verified the correct use of obfuscation decompiled the application and manually looked for obfuscation features. However, all mentioned the manual use of Apktool [53] instead of using Android Studio's integrated APK Analyzer feature. 11% of the developers said they trusted Android Studio's toolchain and its logfiles. Some developers (1.5%) said they verified the correct use of obfuscation by comparing the size of the non-obfuscated with the obfuscated version of an application.

Concerning the 148 Developers who used obfuscation at least once before, we asked them for the tools they used. Most developers (85.8%) previously used ProGuard. Second most popular answer with 8.1% was the now deprecated Jack toolchain. Jack relies on the ProGuard configuration format and mostly mirror ProGuard's obfuscation features while missing some of the more advanced configuration options, such as class name overloading or renaming of resource files. 7.4% used DexGuard, a paid version of ProGuard including some more advanced features such as string encryption. Six developers (4.0%) used ReDex which optimizes .dex bytecode while ProGuard optimizes .class bytecode, but whose renaming functionality closely follows ProGuard's including the same configuration format. 8 Developers also specified other obfuscation tools with only one appearance, like an obfuscation tool built-in to the

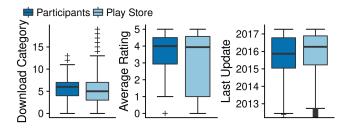


Figure 2: Comparison of app metadata from Google Play with metadata from our participants.

Unity engine.⁴ Overall, ProGuard and ProGuard-like tools are the tools of choice.

4.2 Sampling

To determine the validity of our survey results, we compare metadata of 3,159 apps associated with Google Play accounts from our survey participants with metadata of 2.7M free and paid Google Play applications (cf. Figure 2).⁵ We included the download count (mean store: 5.46, mean sample: 5.89, category 5 corresponds to 100–500 downloads, category 6 to 500–1,000 downloads), the average user rating (mean store: 3.10, mean sample: 3.29) and the date of the last update (mean store: 2015-11-16, mean sample: 2015-09-01) to investigate app age and long-term developer support. Hence, we estimate a rather high validity of our survey results.

4.3 Ethics and Recruiting

Both this survey and the study described in section 7 were approved by the ethical review board of University A in Germany and by the Institutional Review Board of University B in the US. Additionally, the strict data and privacy protection laws in Germany were taken into account for collecting, processing and storing participants' data.

We gathered email addresses from developers who had published apps on Google Play and emailed them an invitation with the options to participate, learn more about our research without priming them, or be blacklisted for the future. We sent emails to 91,185 developers for both the survey and the ProGuard task study; 12,165 (13.4%) of those emails bounced. Before starting, we asked developers to consent to our use and publication of their answers, including code.

4.4 Limitations

As with any user study, our results should be interpreted in context. We chose an online study because it is difficult to recruit "real" Android application developers (rather than students) for an inperson lab study at a reasonable cost. Choosing to conduct an online study allowed us less control over the study environment; however, it allowed us to recruit a geographically diverse sample. Because we targeted developers, we could not easily take advantage of services like Amazon's Mechanical Turk or survey sampling firms. Managing online study payments outside such infrastructures is

 $^{^3}$ cf. https://android-developers.googleblog.com/2017/03/future-of-java-8-language-feature.html

⁴cf. https://unity3d.com/de/

⁵We crawled all relevant metadata from the Google Play website.

very challenging; as a result, we did not offer compensation and instead asked participants to generously donate their time. As might be expected, the combination of unsolicited recruitment emails and no compensation led to a strong self-selection effect, and we expect that our results represent developers who are interested and motivated enough to participate.

In any online study, some participants may not provide full effort, or may answer haphazardly. In this case, the lack of compensation reduces the motivation to answer in a manner that is not constructive; those who are not motivated will typically not participate. We attempted to remove any obviously low-quality data (e.g., responses that are entirely invective) before analysis, but cannot discriminate perfectly.

5 OBFUSCAN: DETECTING PROGUARD OBFUSCATION

While our developer survey indicated that roughly half of participants had obfuscated an app in the past, it did not provide a ground truth view into how apps are obfuscated across the entire ecosystem. To answer this question, we developed the Obfuscan tool to detect various obfuscation techniques in compiled Android apps. Obfuscan is capable of detecting many obfuscation techniques, in particular those used by ProGuard and related tools. We evaluated the efficacy of Obfuscan by conducting a controlled experiment using sample Android applications.

5.1 Obfuscation Detection

OBFUSCAN is able to detect the following general and ProGuard specific obfuscation features:

Name Obfuscation. Names of packages, classes, methods, and fields can be obfuscated by replacing their original names with meaningless labels. For name obfuscation, Obfuscan detects both lower- and upper-case obfuscated names by simulating the obfuscation process of ProGuard and comparing the generated names to the actual names encountered on the app, package, or class level. Obfuscan also considers possible flags such as the usage of mixed-case characters if corresponding strings are detected in the scope.

Method Name Overloading. Related to name obfuscation is the overloading of method names. This technique exploits a feature of the Java programming language that allows for the assignment of the same name to methods with different signatures (i.e. argument types). Using the same obfuscated names for different methods leads to further distortions of code structure. To detect this feature, Obfuscan investigates names that follow the obfuscation pattern and occur multiple times on the same class level.

Removal of Debug Information. To increase the difficulty of inferring application structures, class names, method names, and line numbers can be removed from application metadata. Removal of this metadata prevents the reverse engineering of code structures by intentionally-caused error stack traces. Obfuscan detects missing debug information by parsing and storing the entries of the Java *LineNumberTable* which maps bytecode instruction to source code line numbers. Similarly, the removal of the source file data from classes removes information about the source file where the class (or at least its majority) is defined. Obfuscan detects this

| Feature | TP | TN | FP | FN | MCC |
|---------------------------|-----|-----|----|----|-------|
| Class name obfuscation | 98 | 100 | 0 | 2 | 0.980 |
| Method name obfuscation | 99 | 100 | 0 | 1 | 0.990 |
| Field name obfuscation | 100 | 92 | 8 | 0 | 0.923 |
| Method name overloading | 99 | 100 | 0 | 1 | 0.990 |
| Debug information removed | 100 | 100 | 0 | 0 | 1.000 |
| Annotations removed | 100 | 88 | 12 | 0 | 0.886 |
| Source files removed | 100 | 100 | 0 | 0 | 1.000 |

Table 2: Performance of OBFUSCAN for sample set of 200 APKs. Shown are true positive (TP), true negative (TN), false positive (FP), false negative (FN) predictions, and Matthews correlation coefficient (MCC).

feature by directly accessing the source file attribute of classes and storing the string content of the attribute.

Removal of Annotations. Another feature related to the removal of information strips annotations from classes and methods. This includes annotations such as *Inner Class* for inner classes or *Throws* for methods that contain throw statements. Annotations allow for the retrieval of additional functional context from encountered classes. Obfuscan detects this feature by directly accessing and storing the attribute field of classes.

Not detected ProGuard features. ProGuard includes two features that manipulate resource names and resource content respectively. We decided to omit both features since zero applications in a random sample of 1,000 Android apps from Google Play used these features. Due to their low prevalence on the one hand and the huge performance impact on the detection process on the other hand, we decided to not include them with the goal of significantly speeding up our large-scale analysis.

5.2 Evaluation

After implementing Obfuscan, we set out to evaluate its performance on detecting different obfuscation techniques applied to 100 Android apps. Selecting sample apps for evaluation is non-trivial, as we require the app source code to evaluate apps in obfuscated and non-obfuscated versions. Additionally, distributors of paid tools were hesitant to provide obfuscation samples, likely to keep their obfuscation functionality secret.⁶

For evaluation of Obfuscan we downloaded the source code of a random sample of 100 Gradle-based Android apps published on F-Droid⁷. We note that this app source might bias our evaluation. Google Play apps might be more complex and include more edge-cases (especially since F-Droid condemns the use of non-free dependencies), which in turn will over-report the efficacy of Obfuscan for the evaluation. Since Google Play applications typically are not available as source code, we still think that using F-Droid apps at this point is a more valid choice than relying on self-generated dummy apps for evaluation purposes.

To generate our evaluation app set, we compiled two different versions of each sample app: One version that did not use any

 $^{^6\}mathrm{Despite}$ this, we acquired and tested 26 apps obfuscated with DexGuard, correctly identifying obfuscation in all 26.

⁷List of apps is included in appendix

means of obfuscation and one version that had ProGuard's name obfuscation for all application scopes, method name overloading, debug information removal, annotation removal, and source file removal enabled. Obfuscan correctly identifies nearly all obfuscation features in the dataset of 200 APKs with a low false-positive rate and a high correlation coefficient (cf. Table 2).

We manually investigated false positives and false negatives. Obfuscan falsely detected few class and method names as not obfuscated. In these cases, structures of the app were exempt from obfuscation, e.g. due to classes being marked as an interface. The false positive rate for field names is slightly higher than for other features. This is because ProGuard uses short strings for names (e.g., a and b) that are sometimes used as variables in unobfuscated apps. To detect method overloading, Obfuscan investigates names that follow the ProGuard obfuscation pattern and occur multiple times on the same class level.

Similar to name obfuscation and method name overloading, we manually investigated false positives and false negatives for the information removal features. Obfuscan detects missing debug information by parsing and storing the entries of the Java *LineNumberTable* which maps bytecode instruction to source code line numbers. Attribute and Source file removal is detected by directly accessing and storing the information fields of classes. Obfuscan had no false positives for the debug information and source files removal feature. However, it falsely detected 12 apps using the annotations removal feature. Annotations correspond to code characteristics of classes such as being an inner class or throwing exceptions. This allows for apps that contain no annotations simply by their code structure.

6 OBFUSCAN ANALYSIS RESULTS

We performed a large-scale analysis of 1,762,868 free Android apps from Google Play to investigate real-world use and implications of ProGuard and similar tools. To the best of our knowledge, this is the first large-scale obfuscation detection analysis for Android applications. We downloaded the applications from March 2016 to January 2017. Of those applications, Obfuscan detected the use of ProGuard or functionally equivalent tools (cf. Section 3) in 1,137,228 (64.51%) apps. We found 2,799 (0.16%) apps that use the advanced obfuscation feature of replacing class names with restricted keywords of the Windows operating system (e.g. "AUX", utilized by DexGuard and some Allatori configurations). By analyzing classes.dex files, we found 794 (0.05%) apps that were obfuscated with DexProtector and 207 (0.01%) apps obfuscated with Bangcle.

A large percentage of apps were not intentionally obfuscated by the original developer, but contain third-party libraries that use obfuscation. While some libraries are distributed pre-obfuscated, others ship with ProGuard configuration files to configure obfuscation. The fact that libraries may be obfuscated, but main application code non-obfuscated, is an important distinction for understanding the use of obfuscation throughout the Android ecosystem. In particular, the presence of an obfuscated library does not indicate that core application components are actually being obfuscated.

Android packages follow Java naming conventions, allowing for the identification of larger scopes (e.g. the com.google.ads.interactivemedia.v3.api package can be traced to

| Packages | Unique APKs |
|------------|--|
| 1,919,976 | 681,102 |
| 24,095,920 | 651,952 |
| 1,811,806 | 192,497 |
| 432,856 | 152,668 |
| 135,524 | 135,524 |
| 992,843 | 117,680 |
| 1,309,276 | 106,178 |
| 2,234,609 | 88,242 |
| 491,612 | 87,781 |
| 537,046 | 44,851 |
| | 1,919,976 24,095,920 1,811,806 432,856 135,524 992,843 1,309,276 2,234,609 491,612 |

Table 3: Most prevalent obfuscated libraries by total number of packages and number of APKs containing libraries of the scope. The scope of the libraries is defined by their package name structure.

the *com.google.ads.** scope). Analyzing the scope distribution of obfuscated packages across the apps, it emerges that most of the external library obfuscation stems from a few, popular library frameworks (cf. Table 3).

The most prevalent scopes with their own obfuscation configurations contain libraries commonly used in Android apps. Examples include the Google Ad framework used in the monetization of apps and the Google Mobile Service (GMS) framework for interfacing with Google services such as authentication or search. Commonly obfuscated frameworks not related to Google include the Facebook framework for integrating Facebook access into apps and the FMOD library for audio playback. The Google frameworks for ads and services are commonly used in apps for basic features, adding obfuscated packages to a large number of apps. The presence of these very popular libraries explains why many applications are shown to be obfuscated when examined on an overall package basis, but so few main packages are obfuscated.

While identifying popular libraries is easy to do manually, separating developer code (which may be similar among several apps by the same development team) from less common libraries is far more difficult [3]. To distinguish between apps that are obfuscated by their developer and apps that simply include obfuscated libraries, we also analyze the obfuscation used by the declared main package of the application (A similar distinction of main package vs. other packages was also performed by Linares-Vásquez et al. [34]). This package is used as the universal identifier of the application (e.g. com.google.maps) and is necessarily implemented by the developer, so a choice to obfuscate the main application strongly indicates a choice to obfuscate at least some (if not all) of the original application code.

Our main package analysis found that only 24.92% of apps (439,232 apps) are intentionally obfuscated by the developer. Hence, the vast majority of apps — representing millions of man-hours of development — are not protected using ProGuard as recommended for use in the official Android developer documentation [26].

Our choice of measuring main package obfuscation is not perfect; it is possible that a developer does not obfuscate the main package but obfuscates the remainder of the app. To estimate the frequency

of this practice, we examine how many apps without main package obfuscation have obfuscated packages that do not have multiple occurrences in the overall dataset. We found that only 22,868 apps (1.30% of all apps in the dataset) meet this criteria. We note that an alternative approach to main package analysis would have been to remove third-party library packages after identification with obfuscation-resistant library detection tools such as Libradar [36] or Libscout [3]. This whitelist approach to package filtering would by design miss new or rarely used libraries, so we opted for the conservative approach of main package analysis.

Obfuscan provides the ability to examine use of individual Pro-Guard obfuscation features, and the use of these features for both entire applications and main packages only is shown in Figure 3. The "all package" category is measured as the number of apps containing any package with the obfuscation feature. This includes all libraries and the declared main package. The "main package" category is the number of apps with the obfuscation feature considering only the app's main package. We note that percentages of features used in the main package results are only among those apps with code in the main package.

We see first that class name obfuscation is the most popular feature, with 64.7% of all packages and 24.9% of main packages using it. Looking at other features shows a marked difference in feature use between libraries and main packages. While features that obfuscate method names, field names, and exploit function name overloading are used about as often as class name obfuscation in the all package analysis, they are infrequently used in main packages. One explanation is that library developers have a greater incentive to protect proprietary or sensitive internal APIs.

In addition to name obfuscation features, we also investigated the information removal features of ProGuard for the main package and all packages. As shown in the validation dataset, these features are generally a weaker indicator of obfuscation because their presence depends on characteristics of the code base. For example, the large percentage of main packages without annotations stems from basic code without inner classes, exceptions, or functionality that would require annotations. For all packages, percentages for these features are lower than the name obfuscation features. Library developers may omit these obfuscation features from their configurations to enable debugging by end developers.

Overall, our findings indicate that the vast majority of app developers do not obfuscate their core code, and that even when they do they do not use all of the available obfuscation features. These results might indicate that developers either only obfuscate critical parts of their application or do not understand the entire concept of obfuscation.

By comparing our obfuscation findings with Google Play metadata for all apps that we analyze, we can develop further insights into the use of obfuscation in Android. In this subsection, we consider an app "obfuscated" if classname obfuscation is used, as this is the most common obfuscation feature supported by most obfuscation tools. As in the previous subsection, we distinguish between "all packages" and "main packages" for our analysis. We investigate following trends in app obfuscation: main package obfuscation rate in relation to download numbers; average main package obfuscation by number of apps per Google Play account; and obfuscation by app update date.

| Download Counts | Total Apps | Obfs. Main Package |
|-----------------|------------|--------------------|
| 0+ | 115,683 | 27.30% |
| 10+ | 343,652 | 26.34% |
| 100+ | 499,018 | 24.74% |
| 1,000+ | 383,046 | 24.13% |
| 10,000+ | 234,213 | 23.95% |
| 100,000+ | 80,302 | 25.50% |
| 1,000,000+ | 16,335 | 29.15% |
| 10,000,000+ | 1940 | 36.80% |
| 100,000,000+ | 160 | 50.00% |
| | | |

Table 4: Distribution of main package obfuscation for different download counts. More popular apps have a higher rate of main package obfuscation.

| Apps per Account | Unique Accounts | Avg. Obfs. of MP |
|------------------|-----------------|------------------|
| 1 | 311,908 | 21.83% |
| 2+ | 155,220 | 21.24% |
| 10+ | 27,397 | 26.50% |
| 100+ | 642 | 34.37% |
| 250+ | 112 | 35.29% |
| 500+ | 36 | 68.41% |

Table 5: Average main package obfuscation for number of apps by Google Play account. Accounts with more apps have a higher average rate of main package obfuscation.

App Popularity: Google Play apps range from rarely downloaded one-off weekend projects to popular and complex apps with dozens of developers and millions of installs. Hence, different apps will have different incentives to obfuscate their code. We hypothesized that popular apps would be more likely to obfuscate their code as these apps are often more sophisticated and complex, but also face the greatest risks of plagiarism. To test this hypothesis, we compared the rates of obfuscation for each download count category reported by the Google Play market.

Table 4 shows these results. We find that most apps — the 98.9% $(1,655,914~\rm apps)$ of apps with less than 1 million downloads — are obfuscated at roughly the same rate, ranging from 23.9% — 27.3%. As download counts increase further, we see an increase in obfuscation in the most downloaded apps from 29.15% of apps with more than one million downloads to 50.0% of apps with more than 100 million downloads. While this does confirm our initial expectation, we were surprised that even the most popular apps are only obfuscated on average half of the time.

Obfuscation by Google Play account: Similar to app popularity, we also investigated if the number of published apps per Google Play account plays a role in the decision to obfuscate apps. Our hypothesis was that accounts with more submitted apps either belong to experienced developers or even companies specialized in app development and that apps from these accounts would show a higher obfuscation rate either due to a higher awareness or even previous experience of intellectual property theft or due to a higher perceived investment.

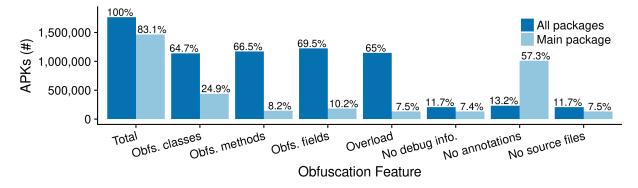


Figure 3: Comparison of obfuscation for different app structures including all packages and main package only. Only apps with an identifiable main package are included in the corresponding category. Overall obfuscation of apps considering all packages is increased due to library obfuscation.

Table 5 shows the results. We find that apps from accounts with less than 100 apps have roughly the same average obfuscation rate between 21.8% - 26.5%. For accounts with 100 or more submitted apps this increases to about 35% and even to 68.4% for accounts with 500 and more apps. This increase in average app obfuscation seems to confirm our hypothesis that experienced developers or specialized companies with a large number of submitted apps use obfuscation more often. A likely explanation for this could be that more experienced developers and companies want to protect their intellectual property further. This could be the results from previous experiences of intellectual property theft, or the result of placing a higher value on their apps, as they are likely an important source of income for professional developers and specialized app companies. **Update Date:** Figure 4 shows how all package and main package obfuscation rates vary when compared to the month of their most recent update; recent updates imply frequent maintenance of apps. ProGuard is distributed with the Android SDK starting August

The figure shows a clear upward trend for both all packages and main packages, though as seen previously the overall obfuscation rate for all packages is much greater than main package obfuscation rate. More recently updated apps are more likely to be obfuscated as well. This could be indicative of greater developer sophistication or greater investment in terms of development time and intellectual property. In any case, it is clear that more recently updated apps are more likely to be obfuscated yet are still obfuscated at a low rate.

2009. The base ProGuard name obfuscation algorithm remained

functionally unchanged, allowing Obfuscan to detect obfuscation

7 ROOT CAUSE ANALYSIS

for all included apps.

The developer survey and app analyses described in the previous sections raised several research questions that we address the following section. In particular, roughly half of surveyed developers claimed to obfuscate their apps, but on average only one quarter of the apps in our study were obfuscated. Given that we showed in subsection 4.2 that our developer sample is representative, why are so few apps in the market obfuscated? We hypothesized that usability of ProGuard may be to blame: developers may think they

are obfuscating their apps correctly, but in actuality are failing to

We ran a controlled online experiment with Google Play developers to investigate challenges when using ProGuard and to identify usability hurdles.

7.1 ProGuard Tasks

To investigate possible usability issues using ProGuard, we invited Google Play developers to apply ProGuard to a given example application and asked them to solve ProGuard specific obfuscation tasks.

We asked developers to solve two ProGuard tasks that involved obfuscating an app in Android Studio. We provided a skeleton app and pointed developers to places in the code where we wanted them to make obfuscation-related decisions. Therefore, developers had to download a zip file containing the skeleton app, import it into Android Studio as an Android application project, work on the tasks, compile the application and upload the binary to our server. We followed this up with a questionnaire, where we asked about the challenges they faced during the tasks.⁸

Task 1 - Configure: The first task required participants to activate and configure ProGuard using an empty configuration file to start with. The goal was to obfuscate an Android app consisting of a single class. Participants were asked to solve this task so we could investigate their ability to complete a basic ProGuard configuration. Possible errors include the inability to activate obfuscation at all or a misconfiguration of ProGuard that disables obfuscation.

Task 2 - Obfuscate and Keep: The second task required developers to activate ProGuard and configure it to obfuscate one class (*SecretClass*), while keeping a second class unobfuscated (*Open-Class*). To solve this task, developers could use ProGuard's -keep flag for the *OpenClass* class.

For the evaluation of the first task, a simple look at the configuration was sufficient, since only one command would enable Obfuscation. To evaluate the second task, we used a subset implementation of the ProGuard Parser that consisted only of the parts

⁸Full questionnaire included in appendix

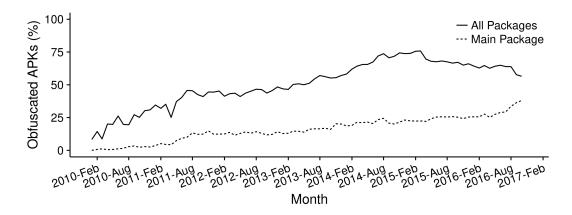


Figure 4: Comparison between the percentage of all obfuscated apps and the percentage of apps with obfuscated main package among the apps updated each month. Update dates are gathered from Google Play metadata and categorized to months. Percentage of apps with obfuscated main package increases for more recent update dates.

required to parse a configuration and detect all possible situations in which *OpenClass* would not be obfuscated but *SecretClass* would.

In the real world, only simple apps can be obfuscated in an approach similar to Task 1. As soon as, e.g. WebViews are present, certain classes have to be kept unobfuscated, or the app will not work.⁹

Of 78 valid participants, 70 (90%) were able to obfuscate the whole app in Task 1. However, only 17 (22%) were able to solve the second task. 11 (14%) of our participants were able to correctly deduce that they had solved or, in 3 (4%) cases, not solved the second task, while 30 (38%) mistakenly thought that they had solved it. The 52 developers who claimed to have ProGuard experience on average performed better compared to the 11 developers without ProGuard experience: from the group with prior experience, 13 (25%) were able to solve the task, while only 1 (9%) from the group without prior experience was able to solve the task. Common errors include not *-keep*ing *OpenClass*, since by default everything is obfuscated, or the use of overly lax rules (e.g. using wildcards), so that *SecretClass* is not obfuscated.

7.2 Analysis Results

The results of this root cause analysis hint at a lack of awareness of the possibility to obfuscate, as well as a lack of risk assessment. In addition, for non-default configurations, there seems to be a usability problem. With the majority of participants (but not all) having heard of obfuscation before and 48% having used it, there is certainly a strong presence of obfuscation in the Android ecosystem. Usage however is low, as seen in Section 6. Usability problems and confusion about the functionality and implications of obfuscation, for example with the case of out-sourced developers not having access to the code if obfuscation is used.

Another interesting finding is that verification of correct obfuscation is either done wrong or requires manual investigation using for example Apktool. Obfuscan can help ProGuard users to verify that obfuscation worked without relying on manual investigation. In future work, we will investigate including Obfuscan as an Android Studio plugin for this purpose.

8 DISCUSSION

To our knowledge, this paper is the first comprehensive analysis of software obfuscation in the Android ecosystem. While earlier work relating to software obfuscation in Android apps focused on reversing the effects or the detection of certain structures despite obfuscation, our work investigates the prevalence of obfuscation and the awareness among developers for potential threats and benefits.

We estimated that the wide spread usage of ProGuard and similar tools would allow us to proxy the general obfuscation in the Android app ecosystem sufficiently.

Security through insignificance? Our large-scale analysis showed that the majority of apps do not take the basic steps to protect themselves. Even for the most popular apps with upwards of 10,000,000 downloads, high risk candidates for obfuscation-related threats, the intentional obfuscation percentage remains below 50%. In our studies, participants assigned a low threat-potential for obfuscation-related attacks to their apps while assuming a greater threat-level for the whole app ecosystem. Through provided write-ins we learned that many developers perceive their apps as too insignificant to ever fall prey to intellectual property theft or plagiarism. This "security through insignificance"-approach could prove fatal to the ever increasing number of small developers in the Android ecosystem.

Optional obfuscation: Another factor that seemingly contributes to the unwillingness of developers to use provided obfuscation tools is the complexity for certain tasks. The unwillingness is based on a low base motivation to begin with, stemming from the negligible

⁹Out of curiosity, we compared the number of apps with obfuscated main packages for whether or not a WebView was present. Of 7,247 apps in our database that contain a WebView class, 1,620 (22.35%) have an obfuscated main package, compared to 24.92% for all apps. However, the first Google results for this topic point to helpful Stack Overflow posts, which might account for this small difference.

perceived personal threat, in combination with cryptic error messages and confusing documentations as soon as tasks increase in complexity.

A certain mind-set seems to have contributed further to the fast rejection of obfuscation: some participants voiced concerns that obfuscation would destroy their already "completed" applications. This view of obfuscation usage as an optional step in app development and not as integral part of the build process could play a larger role in hampering the acceptance of software obfuscation among developers.

Recommendations: Our findings indicate that there are two critical problems preventing widespread adoption of obfuscation in the Android ecosystem. The first is technical, and may have a technical solution: ProGuard is difficult to use correctly. We believe that it may be possible to automatically detect complicating factors (like WebView use) and automatically generate valid ProGuard configurations for developers. If successful, this would allow obfuscation to be enabled by default within Android Studio and other development environments. The second problem is that developers are not motivated to deploy obfuscation given a low perceived risk and high perceived effort. Developers also view obfuscation as an optional, possibly "app destroying" step instead of an integral part of the build process. While improved interfaces and automation for obfuscation may improve the perceptions of effort, more research and education regarding the risks of plagiarism is needed. A technical solution may take the form of new obfuscation techniques or obfuscations applied by the app distributor (e.g., Google Play) instead of relying on developers to protect themselves, their users, and the ecosystem at large.

9 CONCLUSION

Android applications face threats of plagiarism, malicious repackaging, and reverse engineering of valuable intellectual property, and obfuscation tools like ProGuard are an essential protection against these threats. The benefits of obfuscation tools are not limited to the app developers, but extend to app users: obfuscation tools like ProGuard provide benefits to the whole Android ecosystem by sparing end users from confusion and poor user experience from badly plagiarized apps and protecting them against malware in repackaged apps.

This study has presented the first comprehensive analysis of the use of ProGuard for Android apps. In a survey of Google Play developers we found that while most developers are aware of obfuscation tools, they do not see a sufficient benefit and/or find them cumbersome to use. We present and evaluate Obfuscan, enabling us to detect ProGuard obfuscation features in Android application binaries. We applied Obfuscan to more than 1.7 million free Android apps in Google Play, finding that only 24.9% of apps actually obfuscate main application code. To understand why most code is not obfuscated, we conducted a root cause analysis with Google Play developers, asking them to solve some obfuscation tasks. We found that while they managed to configure ProGuard for a simple app, they failed for more complex structures. These findings show that there is a need for tools that are simple yet protect Android apps. In total, our novel results can serve as the foundation to build

more easy-to-use and effective obfuscation tools for application developers.

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APPENDIX

9.1 Online Questionnaire

General Questions

- Which of these have you heard of in the context of Android apps? Please check all that apply.
 (Reverse Engineering, Repackaging of Software, Software Pla
 - giarism, Obfuscation)
- How likely do you think Android apps are ...
 (Reverse Engineered, Repackaged, Software Plagiarism, Obfuscated), scale: (Very Unlikely, Unlikely, Neutral, Likely, Very Likely, I don't know)
- How likely do you think your *own* Android apps are...
 (Reverse Engineered, Repackaged, Software Plagiarism, Obfuscated), scale: (Very Unlikely, Unlikely, Neutral, Likely, Very Likely, I don't know)
- How much do you feel the intellectual property of your *own* Android apps is threatened by...
 - (Reverse Engineering, Software Plagiarism), scale: (Very Unlikely, Unlikely, Neutral, Likely, Very Likely, I don't know)

Terminology 1

- Reverse engineering is:
 - (Translate binary files to source code, Translate source code to binary files, Analysis of pure source code, Analysis of binary files, Reconstruction of app logic, Testing an app's functionality, I don't know, Other [with free text])
- Reverse engineering can be used for:
 (Understanding an app's logic, Circumvention of licence or security checks, Repackaging of an app, Stealing IP addresses, Attacks on Android users who have your app installed, Remote attacks on mobile phones, I don't know, Other [with free text])
- Software plagiarism is:
 - (Repackaging existing software and rebranding it as your own, Use of third party open source code in your software, Imitating software to trick users, Copy pasting code found on the internet, I don't know, Other [with free text])
- Software plagiarism can be used for: (Obtaining software revenue, Distributing disguised malware, Attacking users that have your app installed, Attacking distribution services, I don't know, Other [with free text])
- Obfuscation is:
 - (Making source code unreadable or difficult to understand so only authorized developers can work on it, Making source code unreadable or difficult to understand before compilation, Hiding binaries from the user, Preventing acces to the deployed application, I don't know, Other [with free text])
- Obfuscation can be used for:
 - (Making reverse engineering more difficult, Prevent others from attacking vulnerabilities within your application, Hiding the logic within your application, Optimization of app performance, I don't know, Other [with free text])
- Have you heard of obfuscation before? (Yes, No, Uncertain)
- Have you ever thought about using obfuscation? (Yes, No, Uncertain)
- Did you obfuscate at least once before? (Yes, No, Uncertain)

Obfuscation tools

- Please select all Android obfuscation tools that you have heard of prior to this study.
 - (ProGuard, DexGuard, Jack, DashO, ReDex, Harvester, Other [with free text])
- Please select all Android obfuscation tools that you have used before.
 - (ProGuard, DexGuard, Jack, DashO, ReDex, Harvester, Other [with free text])
- Please select all Android obfuscation tools that you have actively decided against using.
 - (ProGuard, DexGuard, Jack, DashO, ReDex, Harvester, Other [with freetext])
- Which tools do you use to remove unused library code? (ProGuard "Minify", Android Studio "Minify", I remove it manually, I never remove unused library code from my apps, Other [with free text])

Obfuscation 1

- How did you first encounter obfuscation? [Free text]
- How many apps have you worked on? [Number input]
- How many of those where obfuscated? [Number input]
- Why did you use obfuscation on those apps? [Free text]
- Why did you decide against obfuscating apps? [Free text]
- Did you verify that obfuscation was successful? (yes, no)
- How did you verify if obfuscation was successful? [Free text]
- Why did you decide against using obfuscation? [Free text]

9.2 Programming Task

For this Survey, participants were redirected to a howto-page containing an image demonstrating the import, an upload form to reupload the project and the following paragraphs.

About the Study For the Android study, you'll first have to solve two practical tasks. Click here to download an Android Studio Project as a zip file (30 MB). Once the download is complete, you can proceed to the study tasks. While you work on the tasks, please feel free to leave us comments in the project file.

Import the Project Once you've downloaded the zip file, start Android Studio and use File → open to open the project. It might ask you for SDK installation and gradle updates, just apply everything (this process might need to be repeated a few times).

Task 1 Please find out how to activate obfuscation using ProGuard in the Android Project. You're free to use any resources, for example the internet or Android Studio documentation. Activate obfuscation in the project and feel free to leave us comments.

Task 2 Again using any resources you like, obfuscate the project, but exclude "OpenClass" so it is not obfuscated and free to be used as a javascript interface or shared Library. Feel free to leave us comments in the code.

9.3 Programming Task Survey

After completing the programming task, developers were asked to fill out a final survey.

Tasks

Do you think you solved the tasks correctly? (*Task1*, *Task2*), *scale:* (*Yes*, *No*, *I don't know*)
Do you have additional comments on the tasks? [*Free text*]

General Questions

- Which of these have you heard of in the context of Android apps? Plese check all that apply.

 (Reverse Engineering, Repackaging of Software, Software Plagiarism, Obfuscation)
- How likely do you think Android apps are...
 (Reverse Engineered, Repackaged, Software Plagiarism, Obfuscated), scale: (Very Unlikely, Unlikely, Neutral, Likely, Very Likely, I don't know)
- How likely do you think your *own* Android apps are...
 (Reverse Engineered, Repackaged, Software Plagiarism, Obfuscated), scale: (Very Unlikely, Unlikely, Neutral, Likely, Very Likely, I don't know)
- How much do you feel the intellectual property of your *own*
 Android apps is threatened by...
 (Reverse Engineering, Software Plagiarism), scale: (Very Unlikely.

(Reverse Engineering, Software Plagiarism), scale: (Very Uni Unlikely, Neutral, Likely, Very Likely, I don't know)

Terminology 1

- Reverse engineering is:
 - (Translate binary files to source code, Translate source code to binary files, Analysis of pure source code, Analysis of binary files, Reconstruction of app logic, Testing an app's functionality, I don't know, Other [with free text])
- Reverse engineering can be used for:
 (Understanding an app's logic, Circumvention of licence or security
 checks, Repackaging of an app, Stealing IP addresses, Attacks on
 Android users who have your app installed, Remote attacks on
 mobile phones, I don't know, Other [with free text])
- Software plagiarism is:

 (Repackaging existing software and rebranding it as your own,
 Use of third party open source code in your software, Imitating
 software to trick users, Copy pasting code found on the internet, I
 don't know, Other [with free text])
- Software plagiarism can be used for: (Obtaining software revenue, Distributing disguised malware, Attacking users that have your app installed, Attacking distribution services, I don't know, Other [with free text])
- Obfuscation is:
 - (Making source code unreadable or dificult to understand so only authorized developers can work on it, Making source code unreadable or difficult to understand before compilation, Hiding binaries from the user, Preventing acces to the deployed application, I don't know, Other [with free text])
- Obfuscation can be used for: (Making reverse engineering more difficult, Prevent others from attacking vulnerabilities within your application, Hiding the logic within your application, Optimization of app performance, I don't know, Other [with free text])

- Have you heard of obfuscation before? (Yes, No, Uncertain)
- Have you ever thought about using obfuscation? (Yes, No, Uncertain)
- Did you obfuscate at least once before? (Yes, No, Uncertain)

Obfuscation tools

- Please select all Android obfuscation tools that you have heard of prior to this study.
 - (ProGuard, DexGuard, Jack, DashO, ReDex, Harvester, Other [with free text])
- Please select all Android obfuscation tools that you have used before.
 - (ProGuard, DexGuard, Jack, DashO, ReDex, Harvester, Other [with free text])
- Please select all Android obfuscation tools that you have actively decided against using.
 (ProGuard DexGuard Tack DashO ReDex Harvester Other with
 - (ProGuard, DexGuard, Jack, DashO, ReDex, Harvester, Other [with freetext])
- Which tools do you use to remove unused library code? (ProGuard "Minify", Android Studio "Minify", I remove it manually, I never remove unused library code from my apps, Other [with free text])

ProGuard

- What do you use Proguard for? (Testing, Minifying Code, Optimization, Obfuscation)
- After using Proguard, how did you verify that it achieved its goal?
 - (I do not verify that Proguard worked, Reverse Engineering, Other [with free text])
- Why have you never used Proguard before?
 (No need, Never heard of it, Too complicated, I have other tools, Other [with free text])

9.4 Evaluation APKs

```
a2dp. Vol_126_src-release.apk,
app.varlorg.unote_7_src-release.apk,
at.bitfire.gfxtablet_5_src.apk,
at.linuxtage.companion_9_src.apk,
au.com.wallaceit.reddinator_52_src.apk,
axp.tool.apkextractor_1_src.apk,
be.brunoparmentier.dnssetter_3_src.apk,
be.digitalia.fosdem_700136_src.apk,
be . quentinloos . manille_2_src .apk .
be.uhasselt.privacypolice_9_src.apk,
biz.codefuture.svgviewer_8_src.apk,
br.usp.ime.retrobreaker_5_src.apk,
ca.rmen.android.frenchcalender_192_src.apk,
ca.rmen.android.networkmonitor 12804 src.apk.
                                                           14
ca.rmen.android.poetassistant_182_src.apk,
ca.rmen.android.scrumchatter_10302_src.apk,
                                                           16
ca.rmen.nounours_340_src.apk,
cat.mvmike.minimalcalendarwidget_1_src.apk,
                                                           18
ch.blinkenlights.android.vanilla_10430_src.apk,
                                                           19
ch.corten.aha.worldclock_44_src.apk,
ch.ihdg.calendarcolor_4_src.apk,
click.dummer.textthing_18_src.apk,
co.loubo.icicle_4_src.apk,
com.aaronjwood.portauthority_35_src.apk,
                                                           24
com.actisec.clipcaster_48_src.apk,
                                                           25
com.adam.aslfms_40_src.apk,
```

```
com.agnibho.android.solarcompass_1_src.apk,
                                                          27
com.akop.bach_120_src.apk,
com.alexkang.bluechat_2_src.apk,
                                                          29
com.alexkang.loopboard_19_src.apk,
                                                          30
com.amabyte.vtucslabmanual_1_src.apk,
                                                          31
com.anddevw.getchromium_20160614_src.apk,
                                                          32
com.app.missednotificationsreminder_1801010500_src.tar.gz 33
     -v14-release-v1.1.5.apk,
com.axelby.podax_63_src.tar.gz-release.apk,
com.blanyal.remindly_2_src.apk,
com.bleyl.recurrence_23_src.apk,
com. briankhuu. nfcmessageboard_13_src.apk,
com.bytestemplar.tonedef_16_src.apk,
com. casimirlab.simpleDeadlines_19_src.apk,
com.catchingnow.tinyclipboardmanager_57_src.apk,
com.claha.showtimeremote_2_src.apk,
com. cr5315. cfdc_27_src.apk.
com.danielkim.soundrecorder_5_src.apk,
                                                          43
com.daviancorp.android.mh4udatabase_9_src.apk,
com.developfreedom.wordpowermadeeasy_12_src.apk,
com.dimtion.shaarlier_20_src.apk,
com.dnielfe.manager_67_src.apk,
com.dnielfe.manager_67_src-release.apk,
com.doomy.overflow_4_src.apk,
com.doomy.torch_11_src.apk,
com.doomy.torch_11_src-release.apk,
com.ds.avare_230_src.apk,
com.easwareapps.micopi_32_src.apk,
com.easwareapps.quoter_3_src.apk,
com.easwareapps.quoter_3_src-release.apk,
com.easwareapps.transparentwidget_2_src.apk,
com.ebaschiera.triplecamel_5_src.apk,
com.ecuamobi.deckwallet_100_src.apk,
com.eibriel.reddot_3_src-release.apk,
com.enrico.filemanager_4_src-release.apk,
com.gelakinetic.mtgfam_43_src-release.apk,
                                                          61
com.gunshippenguin.openflood_9_src-release.apk,
com.jorgecastillo.kanadrill_28_src-release.apk,
                                                          63
com.jparkie.givesmehope_6_src-release.apk,
com.markusborg.test_17_src-release.apk,
com.moonpi.swiftnotes_9_src-release.apk,
com.morlunk.mumbleclient_73_src-release.apk,
com.mridang.speedo_2_src-release.apk,
com.omegavesko.sutransplus_1_src -release.apk,
                                                          69
com.samsung.srpol_9_src -release.apk,
com.serwylo.lexica_904_src-release.apk,
com.simplemobiletools.applauncher_4_src-release.apk,
com.simplemobiletools.calendar_17_src-release.apk,
com.simplemobiletools.draw_9_src-release.apk,
com.simplemobiletools.notes_9_src-release.apk,
com.tjm.stripepaper_2_src-release.apk,
                                                          76
com. vlille.checker_611_src-release.apk,
com.workingagenda.devinettes_1_src -release.apk,
cz.eutopia.snooperstopper_4_src-release.apk,
de. hoffmannsgimmickstaupunkt_16_src.tar.gz-release.apk,
de.naturalnet.zahnarztgeraeusche_1_src-release.apk,
de.\ onyxbits.\ droidentify\_3\_src.tar.gz-release.apk\,,
ee.ioc.phon.android.speak_1206_src-release.apk,
free.rm.skvtube.oss_1_src-release.apk.
fr.tvbarthel.apps.cameracolorpicker_7_src-release.apk,
indrora.atomic_21_src-release.apk,
IthakaBoardGame-release.apk,
me.anuraag.grader_3_src-release.apk,
min-cal-widget-release.apk,
net.sf.times_37_src-release.apk,
networkmonitor -1.28.4 - foss-release.apk,
nwswidget-release.apk,
                                                          92
org.androidpn.client_20160415_src-release.apk,
org.legtux.m_316k.fortune_1_src-release.apk,
                                                          94
```

```
org.transdroid.lite_227_src-release.apk, 95
org.transdroid.search_28_src-release.apk, 96
org.xphnx.ameixa_37_src-release.apk, 97
sony.hidden.servicemenu_2_src-release.apk, 98
uk.co.ashtonbrsc.android.intentintercept_224_src-release.99
apk,
yellr.net.yellr_android_1008_src-release.apk
```