A Longitudinal Study of App Permission Usage across the Google Play Store

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ABSTRACT

Although there are over 1,600,000 third-party Android apps in the Google Play Store, little is known about how their individual permissions requirements have evolved over time. This work focuses exclusively on dangerous permissions, i.e., those permissions that guard access to sensitive user data. By taking quarterly snapshots of the Google Play Store over a one year period, we characterise changes in the number and type of dangerous permissions required by Android apps when they are updated, to gain a greater understanding of the evolution of permission usage in the Android app ecosystem. We found that 13.8% of updated apps (approximately 30,000) asked for additional permissions every three months. This is almost double the number of apps that asked for less permissions over the same period of time. Wor- ryingly, we made statistically significant observations that free apps and very popular apps were more likely to ask for additional permissions when they were updated. Additionally, we found that updates to approximately 42% of apps caused them to require additional permissions, but with no apparent increase in functionality to the end-user.

Categories and Subject Descriptors

D.4.6 [Operating Systems]: Security and Protection—Access controls

Keywords

Android; permission evolution; Google Play Store

1. INTRODUCTION

Android is the most popular mobile operating system with 84.7% market share as of 2015 Q3, outpacing its nearest rival, iOS, at 13.1% [5]. This domination is fuelled by a myriad of app developers, devices, and consumers existing in a symbiotic relationship known as the Android ecosystem. Nielson reports that the average consumer uses over 26 different apps per month, spending more than one hour per day interacting with their smartphone [8]. This explosion in smartphone usage has been fuelled, in part, by the ease with which end-users can obtain third-party apps to extend the functionality of their devices. App marketplaces stand at the center of the ecosystem, acting as repositories for a plethora of apps, and providing convenient search and download facilities to satisfy the consumers’ appetite. The Google Play Store is the largest (and only official) Android marketplace, boasting in excess of 1,600,000 apps [10].

App developers build apps and release them as either free or paid apps. Free apps usually contain advertisements for monetization while paid apps have an initial charge that must be paid to the developer before the app can be downloaded. To deliver advertisements (ads), apps usually contain ad libraries which fetch and deliver ads. For maximum monetization, ads are targeted to particular user based on their demographic information and/or interests. Thus, apps with more sensitive access to a user’s data may be more profitable to app developers, since they can leverage this additional data for better user profiling, and even maliciously sell the data directly to third-parties.

Problem Scope. The Android OS takes a permission-based approach to guard access to private user data and sensitive APIs. Throughout this paper, we focus exclusively on dangerous permissions, i.e., those permissions that guard access to a user’s confidential data [2]. For this reason, we hereafter refer to dangerous permissions as simply permissions. The permissions required by an app usually relate to the provision of the app’s functionality, but some apps are intentionally over-privileged to facilitate greater access to a user’s personal data. Over-privileged apps threaten privacy by requesting permissions beyond what is needed for app functionality, and can also be a threat to security in cases such as a confused deputy attack [4]. Since Android 6.0, users are no longer forced to accept (or reject) permissions in their entirety at install-time, and can now accept (or reject) permissions individually at run-time. This offers added control, but many users continue to accept permission requests blindly due to conditioning or lack of understanding.

We are motivated to study app permission evolution across the entire Google Play Store, to quantify the extent to which a potential loss of privacy/security happens as new versions of apps are released into the app ecosystem. Previous research efforts have looked at permission evolution on the Android platform itself [3], or the evolution of permission usage in Android ad libraries [3], without looking at the changes in permission usage at the app level or across the entire Google Play Store.
Contributions. Our paper makes the following contributions to the literature:

- An understanding of permission evolution across approximately 1,600,000 apps in the Google Play Store over a one-year period.
- An analysis of the number and types of permissions that are being added to (or removed from) apps, and how app attributes (such as cost or popularity) contribute to their likelihood of adding permissions.

The rest of this paper is organised as follows: Section 2 describes our dataset and the data collection methodology; Section 3 presents our findings on permission usage and evolution across the dataset; Section 4 discusses our results; Section 5 surveys related work; and finally Section 6 concludes the paper.

2. DATASET DESCRIPTION

For our long-term analysis of permission evolution, we needed data on all the apps in the Google Play Store. The Google Play Store Crawler (GPSC) project [7] is concerned with exactly this, but unfortunately does not collect data on permission usage. Thus, we built our own crawler that retrieved full app data (including permission usage) from the Google Play Store, by leveraging the list of apps from the GPSC project. Our first snapshot of the Google Play Store was taken in March 2015 with subsequent snapshots taken every three months (quarterly) after the initial snapshot. The most recent snapshot used in our analysis is that of March 2016, for a total of five snapshots (March-2015, June-2015, September-2015, December-2015, March-2016) over a one-year period.

In taking snapshots, our intention is to have then entire store crawled as quickly as possible. To this end, we developed a cloud-based crawler, with geographically distributed worker nodes fetching app data and returning it to a command and control server. This is shown in Fig. 1. Our worker nodes make app store queries with random valid User-Agent strings and are rate limited to 3 requests/second, to prevent blocking by the Google Play Store. Using a small-scale deployment with 3-4 workers, we can retrieve complete app data from the Google Play Store in less than 48 hours. Our most recent snapshot of the Google Play Store, at the time of writing, contains 25.7GB of data on 1,792,080 apps available for download, and 607,748 apps that are no longer present in the Store.

With each new snapshot of the Google Play Store that we prepare to take, we carry-over the entire list of apps from the previous snapshot, and append any new apps that have been added to the store. Our system is informed of new additions to the Store from the GPSC project and our own crawlers. Apps that have been removed from the Google Play Store remain in our database, with an indicator that they are no longer available. Thus the list of apps in each of our snapshots monotonically increases as time progresses.

3. RESULTS

In this section, we start with a cross-sectional overview of apps and permissions in the Google Play Store, followed by our longitudinal analysis of the data.

Fig. 2 shows the popularity of permissions across all apps. The most popular permissions relate to reading from/writing to external storage on a device (58.9%/58.3% respectively), reading the current state of the device (33.8%), and getting the user’s exact location (24.8%). Fig. 3 shows the number of permissions used across all apps. The largest number of apps (29.4%) used no permissions, while using two (16.5%) and three (14.2%) total permissions was most common among apps that used permissions.

Fig. 4 shows the average number of permissions used by apps based on the category that they were listed under. ‘Communication’ and ‘business’ were the most permission-hungry categories, using an average of 4.9 and 4.7 permissions respectively. The other end of the spectrum was predominantly games, with the overall least permission-hungry category of app being ‘GAME PUZZLE’ using an average of 1.6 permissions per app. Fig. 5 shows how many per-
missions were used based on the number of downloads that an app had. Up to 1,000,000 downloads, the average app used approximately 2.5-3 permissions. With the exception of apps having 500million-1billion downloads, apps with 10,000 downloads and above had permission usage that monotonically increased from 2.5 up to 8.3 permissions, on average.

### 3.2 Longitudinal Analysis

Fig. 4 shows how permission usage changed across the Google Play Store over the one-year period of March-2015-March-2016. We analysed permission usage based on the number of downloads of an app. We divided apps into three categories based on their total number of downloads: 1-1K (low downloads), 1K-1M (medium downloads), and 1M-500M (high downloads). We ignored apps with more than 500M downloads because they represented a negligible fraction of the Google Play Store. Overall, we found that apps in the low downloads category had the highest change (an increase) in permission usage over the one-year period, going from 2.5 to 2.9 permissions. Apps in the medium downloads category went from 2.6 to 2.7. Notably, apps in the high downloads category used an approximately constant number of permissions, averaging 4.57 over the one-year period.

We analysed permission increase/decrease at the app level to understand how many permissions individual apps were adding or removing when they were updated. We observed that a majority (87%) of apps did not get updated between snapshots of the Google Play Store. Only 11% of apps were updated and we were unable to tell for 2% of apps because their current version varies depending on device (thus exact version information was not available from the Google Play Store). In the following analysis, we include only those apps that were updated, to understand what changes in permission usage, if any, were made. Table 1 shows the breakdown of permission changes across our quarterly snapshots for those apps that were updated. In the table, each date shows the permission changes between that snapshot and the previous snapshot. The table details the amount of permissions that were added/removed across the apps that were updated. From the table, the vast majority of apps (on average 78.7%) did not have any change in permission requirements across each snapshot. For apps that did have changes, the most likely change (7.5% of apps on average) was to add one new permission (+1). Averaging permission changes across our one-year of data, 13.8% of apps added one or more new permissions every 3-months, while only 7.5% of apps removed one or more permissions. That is, ap-

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1Only 25 apps (of approximately 1,600,000) in our snapshot of the Google Play Store have more than 500M downloads at the time of writing.

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See footnote 1.

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Due to rounding errors, some of the columns in Table 1 do not sum to exactly 100.00%.
approximately twice (1.8) as many apps required an increased number of permissions than those that required a decrease, over the studied period.

We analysed the permissions that were added to apps when they were updated, to understand the potential erosion in privacy caused. This result is presented in Fig. 7. From the figure, we can see that the Top 5 permissions that were added allowed apps to access the list of accounts (in the Accounts Service) on a device, access a user’s location, read from/write to the device’s external storage, and access the device’s state. Fig. [5] shows which permissions were removed the most. The most commonly removed permission was WRITE_CALENDAR, covering approximately one-quarter of the incidents of permission removal from apps.

Hypothesis 1: Free apps are more likely to add new permissions than paid apps. Table 2 breaks down incidents where permissions were added, broken down by whether an app was free or paid.

| Change         | Jun-15 | Sep-15 | Dec-15 | Mar-16 |
|----------------|--------|--------|--------|--------|
| Increase       | 11.71% | 18.33% | 13.78% | 11.39% |
| +6 or More     | 0.23%  | 0.26%  | 0.22%  | 0.19%  |
| +5            | 0.15%  | 0.26%  | 0.25%  | 0.13%  |
| +4            | 0.56%  | 0.91%  | 0.68%  | 0.45%  |
| +3            | 1.27%  | 1.63%  | 1.43%  | 1.01%  |
| +2            | 3.25%  | 5.29%  | 3.98%  | 3.08%  |
| +1            | 6.25%  | 9.98%  | 7.22%  | 6.53%  |
| Decrease       | 6.06%  | 5.37%  | 9.08%  | 9.53%  |

| Change         | 0-6 |
|----------------|-----|
| Decrease       | 0.30%  |
| -1             | 1.82%  |
| -2             | 0.53%  |
| -3             | 0.22%  |
| -4             | 0.13%  |
| -5             | 0.30%  |
| -6 or Less     | 1.00%  |

Table 1: Table showing how permission usage changed between quarters for those apps that were updated. Approximately twice as many apps added permissions than removed permissions.

Figure 7: Breakdown of the newly added permissions across the Google Play Store.

Figure 8: Breakdown of the newly removed permissions across the Google Play Store.

Table 2: Aggregated list of incidents where permissions were added, broken down by whether an app was free or paid.

| Percentage | Free | Free (%) | Paid | Paid (%) |
|------------|------|----------|------|----------|
| Increase   | 49858| 95.7%    | 2233 | 4.3%     |
| 2           | 20011| 94.6%    | 1142 | 5.4%     |
| 3           | 6914 | 97.9%    | 375  | 2.1%     |
| 4           | 164  | 96.8%    | 983  | 3.2%     |
| 5           | 75   | 72.8%    | 28   | 27.2%    |
| Total       | 82304| 95.4%    | 3935 | 4.6%     |

Hypothesis 2: Popular apps are more likely to add new permissions than paid apps. Table 3 breaks down incidents of permissions being added, based on app popularity (whether an app had Low or High downloads). As in Section 3.2, we considered 1-million downloads as the threshold above which an app was placed in the High category. We used a 2-proportion z-test with a sample size of 20,000, and significance level of 0.01 to determine whether there was a statistically significant difference between apps with Low and High downloads when it came to adding new permissions. Our result showed $p < 0.0001$, suggesting that free apps were more likely than their paid counterparts to add new permissions over time.

Hypothesis 3: Frequent downloading of apps indicates an increased willingness to give up privacy. New versions of some apps require additional permissions with no corresponding increase in functionality to the user.

5The discrepancy of 58 between the total number of incidents in Table 2 and Table 3 is caused by errors in the data obtained from the Google Play Store. These errors prevent us from accurately parsing the number of downloads for 58 apps, and thus these apps have been omitted.
Table 3: Aggregated list of incidents where permissions were added, broken down by whether an app had Low or High (more than 1 million) downloads.

| Increase | Low | Low (%) | High | High (%) |
|----------|-----|---------|------|---------|
| 1        | 49719 | 95.5% | 2321 | 4.5%    |
| 2        | 20200 | 95.6% | 938  | 4.4%    |
| 3        | 6869  | 95.5% | 321  | 4.5%    |
| 4        | 3373  | 96.4% | 125  | 3.6%    |
| 5        | 1047  | 95.5% | 49   | 4.5%    |
| 6        | 464   | 95.5% | 22   | 4.5%    |
| 7        | 236   | 96.7% | 8    | 3.3%    |
| 8        | 115   | 92.7% | 9    | 7.3%    |
| 9        | 101   | 98.1% | 2    | 1.9%    |
| 10+      | 257   | 98.1% | 5    | 1.9%    |
| Total    | 82381 | 95.6% | 3800 | 4.4%    |

In other words, some apps are updated to leverage additional permissions but provide no added functionality that would necessitate the use of those permissions. To understand the prevalence of this behaviour, we looked at when apps were updated to see the difference, if any, in their permission usage and their functionality. We used the app store description of an app as a proxy for its functionality. Since app stores use keywords from an app's description in search ranking algorithms, we assume that developers are motivated to update their app descriptions whenever new functionality is added to an app. Following on from this assumption, we deem it suspicious if a new version of an app suddenly requires new permissions without a corresponding update to its Store description or What's New section. To test the prevalence of this phenomena, we analysed permission increases across our year of snapshots and checked for corresponding updates to the Store descriptions or What's New section of apps. Worryingly, we found that approximately 42% of apps that added new permissions did not update their Store description or What's New section. This is cause for concern since it means the only update to these apps was the surreptitious addition of one or more permissions without any indication of new functionality or benefit to the user.

4. DISCUSSION

Our focus throughout this paper was to understand how permission usage in the Android ecosystem evolves over time. We were also interested in understanding whether the cost (free vs. paid) or popularity (number of downloads) of an app had any bearing on the usage/evolution of permissions. We only focused on dangerous permissions, those permissions that guarded sensitive user data. We ignored changes in normal permissions because these permissions, if abused, only cause minor annoyance to a user, as opposed to putting their personal data at risk.

We first looked at the average number of permissions used by apps across the Google Play Store based on the popularity of an app. We found that very popular apps (those with in excess of one million downloads) used more permissions than those with less downloads. This could be due to the fact that they provide more functionality, and hence why they are popular in the first place. Over the long-term, we observed that less popular apps had a greater the increase in average permission usage. Very popular apps, on the other hand, had fairly consistent permission usage. This could be due to the fact that the very popular apps already used more permissions than less popular apps and thus had less reason to add additional permissions. Less popular apps, in an attempt to gain popularity, could be adding additional features (necessitating additional permissions) in an attempt to attract more users.

We attempted to understand the frequency of app updates and the extent to which permissions were added (or removed) when apps were updated. Unsurprisingly, we observed that the majority of apps (87%) did not get updated between Store snapshots. Of the apps that did get updated, approximately four out of five of them did not have any change in their permission requirements. However, 13.8% of the apps that were updated now needed one or more new permissions. This corresponds to approximately 30,000 apps needing new permissions every three months, in an app store of 1.600,000 apps. We also discovered that apps were more likely to add new permissions than remove permissions, overall pointing to a potential erosion in privacy and security.

We conducted hypothesis tests to determine whether there was a correlation between the cost of an app and the likelihood of that app adding new permissions. We found statistically significant evidence that free apps were more likely to add new permissions than paid apps. This could be as a result of free apps trying to provide more targeted advertisements to users, and thus needing access to additional profiling data. We also tested whether the popularity of an app had an impact on how likely the app was to add new permissions. Our data showed that more popular apps were more likely to add new permissions. This is worrying, because it means that a large segment of users in the Android ecosystem are potentially exposed to additional privacy/security risks simply as a result of using and updating popular apps.

We analysed whether new versions of apps were providing new functionality to users when they requested additional permissions. By leveraging an app's description as a proxy for its functionality, we observed that approximately 42% of apps added new permissions but did not update their Store description. The lack of an update in Store description does not prove that there was no increase in app functionality. Indeed, an app developer may simply update their app without changing its description or What's New section. However, we believe that app developers would be eager to explain new functionality that was added to their app to make their app more attractive to users and also to provide additional keywords to the search ranking algorithms. Thus we consider this behaviour suspicious.

5. RELATED WORK

Viennot et al. performed the first large scale analysis of the Google Play Store using a tool they call PlayDrone to index and analyse over 1.1 million apps [12]. They decompiled and obtained the source code for over 80,000 free apps. The authors characterised the content of the Google Play Store, measured library usage in apps, identified duplicate apps, and uncovered weaknesses in how authentication was implemented in many apps. Our work is similar in that we take snapshots of the entire Google Play store as well, but differs in that our analysis is longitudinal and is concerned with gaining a greater understanding of how app permission usage evolves over time and the potential impacts of this
phenomenon on smartphone privacy and security.

More in line with our work, Book et al. do a longitudinal analysis of Android ad library permissions \cite{3}. The authors investigate a sample of 114,000 apps to build a chronological map of permission usage in Android ad libraries. Their analysis reveals that indeed permission usage by ad libraries has increased in recent years and, worryingly, that these ad libraries have access to permissions that pose risks to user privacy and security. This work is a step in our direction, but since ad libraries request a subset of the permissions required by an app, it fails to capture the full picture of the risk to devices that come from apps on a whole. Our work expands by taking a holistic approach to looking at permission usage across the entire app.

Wei et al. go in a tangential direction and characterise permission evolution on the Android platform itself \cite{13}. They look at changes in the Android permission model since its first commercial release for smartphones in 2008. They find that permission growth is aimed towards offering access to new hardware features and not towards offering more fine-grained control to a user. From a sample of 237 third-party apps, the authors discover that apps are over-privileged and use dangerous permissions. The authors also characterise the dangerous permissions required by pre-installed apps (which are difficult to remove) and argue that the evolution tends to favour the vendors and not the users. The authors focus mainly on permission evolution within the Android platform itself, while our work focuses on looking at permission evolution across apps in the Android app ecosystem as a whole.

Along similar lines, Vidas et al. \cite{11} propose a tool to help mitigate permission creep by assisting developers to enforce the principle of least privilege \cite{9}. Their tool, implemented as an IDE plugin, analyses app source code and helps the developer to understand the minimum permissions required for their application to run. The authors focus on developers who inadvertently request too many permissions for reasons such as lack of understanding or expected future use. They create a permission-API database which understands the permissions required for particular function calls. From this database, their tool can statically analyse source code and manifest files to identify extraneous permissions. Using their tool, the authors examine 34,000 free third-party apps and find that more than 4\% have duplicate permissions in the manifest files. This underscores the idea that developers are not cautious enough when requesting permissions. Building on this, our work takes a look at whether there is a systematic permission creep across apps in the Google Play Store and whether conclusions can be drawn about the reason for this permission creep.

6. CONCLUSIONS

In this paper, we did a longitudinal analysis of permission evolution in apps by taking quarterly snapshots of the Google Play Store over a one-year period. Our analysis showed that the average number of permissions used by apps increased over the one-year period, with less popular apps having a greater increase. We observed that a majority of apps do not get updated between snapshots, and of those that get updated, a majority do not have any changes in their permission requirements. However, of the apps that do have changes in their permission requirements, the most likely change is the additional of a new permission. We observed almost twice as many apps adding new permissions as apps removing permissions.

We did hypothesis testing and observed that free apps and popular (apps with more than one million downloads) apps were more likely to add new permissions over time. The addition of new permissions is not inherently bad, as many apps have legitimate reasons to request additional access to user data. However, many apps are also known to abuse their granted permissions for the purposes of profiling users and/or directly stealing their data. We have observed a trend across the Google Play Store for apps to add new permissions over time. In drawing this phenomenon to the attention of the research community, we hope to generate additional interest in the area, so that appropriate strategies can be developed to keep sensitive user data safe, as smartphones continue to become a critical part of our lives.

7. ACKNOWLEDGMENTS

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