Why Data Deletion Fails? A Study on Deletion Flaws and Data Remanence in Android Systems

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Smart mobile devices are becoming the main vessel of personal privacy information. While they carry valuable information, data erasure is somehow much more vulnerable than was predicted. The security mechanisms provided by the Android system are not flexible enough to thoroughly delete sensitive data. In addition to the weakness among several provided data-erasing and file-deleting mechanisms, we also target the Android OS design flaws in data erasure, and unveil that the design of the Android OS contradicts some secure data-erasure demands. We present the data-erasure flaws in three typical scenarios on mainstream Android devices, such as the *data clearing flaw*, *application uninstallation flaw*, and *factory reset flaw*. Some of these flaws are inherited data-deleting security issues from the Linux kernel, and some are new vulnerabilities in the Android system. Those scenarios reveal the data leak points in Android systems. Moreover, we reveal that the data remanence on the disk is rarely affected by the user's daily operation, such as file deletion and app installation and uninstallation, by a real-world data deletion latency experiment. After one volunteer used the Android phone for 2 months, the data remanence amount was still considerable. Then, we proposed *DataRaider* for file recovering from disk fragments. It adopts a file-carving technique and is implemented as an automated sensitive information recovering framework. *DataRaider* is able to extract private data in a raw disk image without any file system information, and the recovery rate is considerably high in the four test Android phones. We propose some mitigation for data remanence issues, and give the users some suggestions on data protection in Android systems.

CCS Concepts: • **Security and privacy → Mobile platform security;**

Additional Key Words and Phrases: Data recovery, secure deletion, file carving, mobile security

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1. INTRODUCTION

The popularity of smart mobile computing platforms, such as in Android devices, has changed the way that people process information. Developers have built myriad attractive and innovative applications for smartphones to add convenience and fun to

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people's lives. They also store a great deal of sensitive data from those services, such as cameras, telephony, and GPS. With malicious intention, attackers might retrieve valuable information. For instance, mobile social network apps help get connected with friends; online banking services help keep track of financial status; mobile health apps help manage private information about diet, medication adherence, stress, smoking cessation, and parental and infant care; and photos can be uploaded to the Cloud for storage. All of these services build up a digital figure of a person in the new age of the Internet. Therefore, plenty of privacy information is stored on smart mobile devices [Azfar et al. 2015, 2016a, 2016b], which are not considered to be the perfect security vessel for sensitive information.

Being the most popular mobile operating system, Android has long been a prime source of criticism regarding privacy leaks. The major issue is how the Android system and applications manipulate the data, such as when and where the data has been read, modified, or transmitted. Studies in Heuser et al. [2014], Bugiel et al. [2013], Xu et al. [2012], Jeon et al. [2012], Enck et al. [2014], Arzt et al. [2014], Backes et al. [2013], and Wu et al. [2014] have discussed different aspects, including hardware characteristics and OS features, that would directly cause the failure in secure data operations that leads to the privacy leak. Yet seldom do they notice that data remanence after insecure deletion could also be a threat since Android does not provide enough clarify regarding how third-party applications process user data stored on a mobile device.

For example, secure deletion on flash memory is well studied [Wei et al. 2011; Reardon et al. 2012, 2013]. The safety of the data is not well protected by the underlying processing mechanism of the OS, especially Android. Data remanence caused by improper but stealthy data deletion behavior of the Android system is worth studying to guide a more secure data erasure.

The major work of this article is twofold. The first part of our work discusses the data remanence caused by some design flaws of the Android system. One of the main reasons for data remanence is the ignorance of the Android OS on data deletion. Although data remanence and its recovery have been analyzed in many previous studies [Kung 1993; Bauer and Priyantha 2001; Quick and Choo 2013a, 2013b], the Android security mechanism still does not consider this issue even in the latest version. We found that Android 6.0 and *ext4* filesystem are still not able to provide secure deletion. Another issue is the fragmentation of the Android OS. Android devices come in vastly different performance levels and screen sizes. Further, there are various different versions of Android currently running on those devices, which intensifies the fragmentation. Myriad versions of Android OS introduce various implementations, for example, the way to manipulate an embedded SD card, unlock the bootloader, modify the *recovery* subsystem, and so on. Under certain circumstances, the proprietary implementations contradict the privacy protection requirements, and further initialize the nonperceptible privacy residues.

Does it mean that using other files to overwrite the original files would guarantee secure deletion? According to our data deletion latency experiment, the answer is no. By tracking data remanence on the Android devices of several test volunteers, after more than 2 months usage of the phone, the observed data remanence has an over 40% chance of staying intact.

After thoroughly studying an exhibition of the data deletion latency and the impact of this underlying file system design flaw, we construct several attack contexts to evaluate the related impact. Previous studies mainly focus on physical layer factors and are concerned less about system-level issues. We argue that it is hard to acquire a completely secure data deletion mechanism without considering system-level issues carefully. We study the design policy and data operation interfaces related to three aspects of privacy erasure on the most prevalent version of the Android OS with five mainstream Android devices.

To better evaluate the remanence of the deletion operation, we propose *DataRaider*, a file-carving tool for recovering SQLite files from crumbs. Then, the ethical attacks have successfully recovered over 80% of the data from the data remaining on the device. It allows us to obtain deleted emails, WeChat chat logs, and even allows impersonation attacks on an online payment account. We also analyze how much information could be retrieved after a vulnerable *factory reset* operation. The results indicate that most devices are of high privacy disclosure risk due to the deployment of the third-party *Recovery* system. Approximately 99% of the original data has remained after an improper data-erasure process, which is considered to be a significant failure in private data erasure operations.

The contributions of this article are as follows:

(1) We first present the data operations in several system layers, including flash memory, file systems and the *Recovery* subsystem. We analyze the vulnerabilities or design flaws that cause data deletion deficiency. As we have discovered, the flash memory attempts to prolong its lifetime by balancing the write operations on more units. In addition, the *TRIM* command in some Android versions worsens the situation by poor implementation on deleting the data from the flash memory. Both guarantee longer data remaining time and higher probability of its recovery. We also discuss the partition clearing failure caused by careless implementation of file deletion in the *Recovery* subsystem.
(2) Based on the discoveries and analysis results, we construct a series of attacks of private data retrieving. We mainly focus on three most common private data deletion scenarios: *app data clearing*, *app uninstallation*, and *factory reset* operations. Our attacks successfully retrieve over 80% of deleted private data from the first two attacks. The implementation flaw in factory reset leads to the success of our attack on recovery of private data directly from the flash image. In 3 out of 4 experimental mobile phones, we have retrieved over 90% of the data from the cleared partitions.
(3) We also design and implement an advanced data-remain evaluating framework based on the file-carving technique. The implemented *DataRaider* is able to extract private data in a raw disk image without any file system information, and the recovery rate is considerably high in the four test Android phones. According to our experiments, the performance of *Dataraider* is comparable with mainstream file-carving tools.

The rest of this work is organized as follows. Section 2 introduces essential background related to the data storage and the file operations. Section 3 exhibits three aspects of the system design defects that cause the insecurity of data. In Section 4, we examine the current state of deletion flaws on Android and the techniques that we use to retrieve sensitive information out of the data remain. Section 5 proposes a mitigation method along with suggested use and performance analysis. Section 6 describes the related work. Section 7 presents our conclusions.

2. STORAGE SYSTEM BACKGROUND

2.1. Linux File System

2.1.1. Ext4 File System. The ext4 file system is the most common default file system in Linux distributions such as Mint, Mageia, Ubuntu, and Android. It is a *journaling* file system for Linux, developed as the successor to ext3 [Wikipedia 2015].

The ext4 file system manages the file storage as a series of block groups, and the files allocate storage space in units of *blocks*. A block is a group of sectors whose size

Table I. Layout of a Standard Block Group of Ext4

Group 0 Padding	*ext4 Super Block*	*Group Descriptors*	*Reserved GDT Blocks*
1024B	1 block	many blocks	many blocks
Data Block Bitmap	*inode Bitmap*	*inode Table*	*Data Blocks*
1 block	1 block	many blocks	many more blocks

varies between 1KiB and 64KiB. Blocks are, in turn, grouped into larger units called block groups. Block size is specified at mkfs time and typically is 4KiB.

To decrease performance loss, the block allocator tries to keep each file's blocks within the same group, thereby reducing seek times. With the default block size of 4KiB, for instance, each group will contain 32,768 blocks, for a length of 128MiB. The number of block groups is the size of the device divided by the size of a block group [Pomeranz 2010].

The layout of a standard block group is depicted in Table I.

The ext4 file system has a journal that records updates to the file system metadata before updates. In the case of system crash, the OS reads the journal, then either reprocesses or rolls back the transactions in the journal. Example metadata structures in Table I include the directory entries that store file names and *inodes* that store file metadata. The journal contains the full block that is updated, not just the value being changed. When a new file is created, the journal should contain the updated version of the blocks containing the directory entry and the *inode*. Due to its property, the journal is very useful for recovering files even after a format operation. On file deletion, the file system deletes only the journal information; however, the block content still remains in the storage system. It gives the hackers a chance to recover the file.

2.1.2. Ext4_utils Security Issues. A root cause of the failure in wiping the metadata is the ineffective implementation of ext4_utils. The earlier version of *ext4_utils* by default wiped the partition when performing the format operation. It wiped only the index of the files, leaving the metadata. However, it added the explicit wipe option (on January 28, 2011); this change has also been merged into the Android Open Source Project. In detail, this change adds a *-w* option to explicitly inform the *make_ext4fs* tool to wipe the partition before formatting. The original intention is to use the *BLKSECDISCARD* ioctl to erase the partition so that it avoids leaving any data content. As a result, if the wipe option -w of *make_ext4fs* is ignored, the formatting will not wipe the old data on partition, as it will be deliberated in the Android *Recovery* subsystem.

2.2. Android Storage System

2.2.1. Flash Memory Issue. Unlike the commodity personal computer, which uses magnetic storage devices such as hard drives, Android smartphones and tablets mainly store data on the SoC with an embedded Multimedia Controller (eMMC) and the Solid State Driver (SSD) as the internal memory [Wikipedia 2014]. The type of the internal memory is primarily the NAND type flash memory [Wikipedia 2014]. One characteristic of NAND flash is that its I/O interface does not provide a random-access external address bus. Instead, data must be read on a blockwise basis, with typical block sizes of hundreds to thousands of bits. Even if the erased data is part of a block, the entire block should be overwritten. As a result, for a NAND flash memory, the deleted data is not thoroughly erased right away but labeled as *unused* by the system. This characteristic, however, leads to the data remain, obviously. In the only scenario in which the whole block has been overwritten, the goal of thorough data erasure can be fulfilled.

The flash memory has a finite number of program-erase cycles, as most commercially available flash products are guaranteed to withstand around 100,000 P/E cycles before the wear begins to deteriorate the integrity of the storage. The corresponding data-processing mechanism of the OS must consider its physical characteristic and the security-performance trade-off. Experimental results in Reardon et al. [2012] revealed that the deleted data will remain in the flash memory until it is overwritten by other operations. It implies a relatively longer residence time of the private data. The residence time increases with the size of the memory and decreases with the frequency of memory use.

Another issue is that, even if data filling or rewriting is accomplished, it should be carefully deployed to ensure effectiveness. Unlike a traditional hard disk, flash memory has a unique data-writing management characteristic, which prevents the file system from employing an in-place overwriting operation. If the file system commands the storage medium to overwrite an existing data block, the on-board controller of the memory may write the data into a new place while labeling the old data block as *unused*. This implies that the data-remain issue is transparent to the upper layers in Android.

2.2.2. Android File System Partition Specification. Like a normal hard disk drive, the internal storage medium of an Android device can be partitioned. The internal memory usually consists of the following partitions:

—The */system* partition contains the entire Android OS, other than the kernel and the RAM disk. It includes the Android GUI and all the system applications that come preinstalled on the device. This partition is, by default, mounted as read-only, for no data modification is required during runtime.
—The */recovery* partition holds a second bootable Linux system known as the *Recovery* system. The *Recovery* subsystem can be seen as a rescue system allowing basic operations on the device without booting into full Android. If the device enters the recovery mode, the *Recovery* system is activated for performing advanced recovery and maintenance operations, such as OTA update to Android Recovery Wiki 2015 [XDA Developers 2015b].
—The */data* partition, also known as the */userdata* partition, contains the user's data, such as contacts, SMS, settings, and all Android applications installed. If it is erased, the Android system will return to the factory settings. The most valuable private information of the users usually resides in this partition, which makes it the preferred attack object.
—In addition, the */sdcard* partition is special for Android devices. Often, it is not on the internal memory of the device, but rather is on the external SD card. (However, currently, manufacturers integrate the *sdcard* into the main internal memory for performance purposes.) It is used to store nonsensitive files, such as media, documents, and downloaded files. On devices with both an internal and an external SD card, the */sdcard* partition is always used to refer to the internal SD card. For the external SD card, if present, an alternative partition is used, which differs from device to device.

Among those partitions, the */data* partition is the most valuable one for data recovery attacking.

2.2.3. Android Data Deletion. Generally, there are two operations related to data deletion in Android.

The first is the common file deletion operation via system interface. In this case, even when an explicit deleted file retention facility is not provided or when the user does not use it, operating systems do not actually remove the contents of a file when it is deleted unless they are aware that explicit erasure commands are required, such as on an SSD. Instead, they simply remove the file's entry from the file system directory, because this requires less work on a NAND flash memory and is therefore faster, and

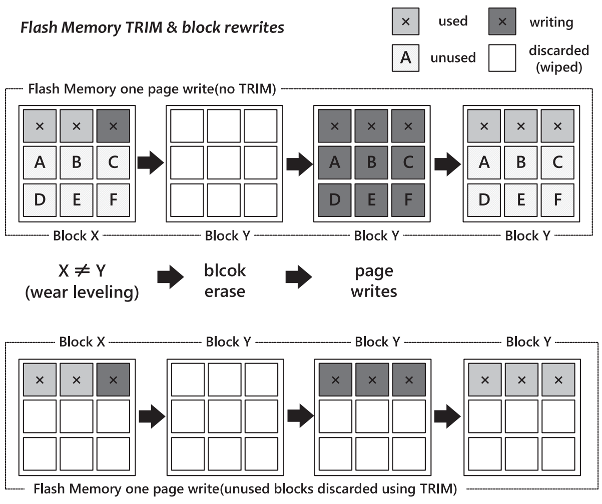

Flash Memory TRIM & block rewrites
used
writing
unused
discarded (wiped)
Flash Memory one page write(no TRIM)
A B C D E F
Block X
Block Y
X ≠ Y (wear leveling)
blcok erase
page writes
Flash Memory one page write(unused blocks discarded using TRIM)

Fig. 1. The TRIM feature.

the contents of the file—the actual data—remain on the storage medium. The data will remain there until the OS reuses the space for new data.

Since Android 4.3, the OS issues the *TRIM* command to let the drive know that it should no longer maintain the deleted data [Bell and Boddington 2010]. *TRIM* is a garbage collection feature that helps negate write performance reduction in flash-based storage devices; *TRIM* negates this by marking deleted data for the SSD controller to erase while the device is idling, making sure that the cells holding deleted data are erased and ready to be written on. Figure 1 shows the process of data deletion with the *TRIM* feature activated.

With the *TRIM* feature, the Android OS informs the device which sectors are no longer used (no longer contain valid data) and that the device does not need to keep data content. Thus, the TRIM command helps to erase data more thoroughly due to its low-level property. However, most current devices are not updated to support this new property; thus, data remains may still exist. Moreover, a side effect of the *TRIM* feature is that it may introduce observable data-deletion latency: the hardware controller may not immediately recycle the data block.

The second operation is the *factory reset* operation for Android. Before an Android device is reused, the owner would like to clear the storage to prevent accidental disclosure of confidential data to the succeeding user. According to our study on the *Recovery* subsystem (see Section 4), doing a *factory reset* is to reset the device to its initial state, including removing all the data from the */data* and */cache* partition. As mentioned earlier, the */data* partition stores almost all the sensitive information related to the user's privacy. This operation triggers a data wiping against the entire partition that contains most of the user's sensitive information. Specifically, the *factory reset* generally asks the storage medium to use its low-level data wiping function (built-in ATA command) to guarantee a secure data deletion.

3. ANDROID DATA-ERASING FLAWS

Note that the protection of privacy should cover the lifetime of the data, which begins from data generation and extends to data transformation, calculation, transmission, storing, until its deletion. Failure at any stage would cause an unexpected privacy leak. To avoid this, a protection mechanism should be imposed throughout these stages. It should be mandatory for the end users to ensure that the private data on a device is protected, and that it is thoroughly and securely erased when a file-delete operation takes place, even if the attackers have the capability of recovering information from metadata.

During its lifetime, the private data could be erased by the system's data-deletion operation in four scenarios: (1) generic file deletion, (2) app data clearing, (3) app uninstallation, and (4) partition clearing. Except for generic file deletion, which is easily observed, the other three operations are out of an app's control. We have found that failures in such data-erasure demands happen whenever the users intend to clear confidential files, uninstall high-assurance apps, and *factory reset* their devices. In the following, corresponding design flaws of these operations are discussed in detail.

3.1. Obscure File Deletion Flaw

The file deletion issue of flash memory is quite simple and well studied: if the file deleting operation of the system has not thoroughly erased the data from the flash memory, the content can be partially or fully retrieved. However, people often focus on generic data deletion and recovery (e.g., recovering data on the sdcard of the device). While this kind of insecure data deletion is well observed and can be enhanced on the Android platform, privileged data's deletion is discussed less often, which is more obscure and may lead to even more sensitive private data leaks.

According to the design specification, the Android app stores its privileged data in */data* partition and the data is protected by Android's sandbox mechanism. The mutual access to this part of the data between applications is restricted; thus, it gives the users an incorrect impression that the applications and the involved data are under protection. However, the deletion operation to this part of data is often obscure. While the sandbox protects the data at runtime, it does not consider the secure deletion when a temporary file or the application reaches its completion. The ways that applications delete files and system uninstall applications both lead to insecure file deletion. Yet the application itself is seldom aware of this data-disposing process and cannot control the deletion. In this situation, the obscurity of this process determines that the privileged data is neither securely disposed of nor properly encrypted. Thus, data remanence happens in a stealthy way.

More seriously, the prerequisite of a secure sandbox is that the root privilege has not been overwhelmed, or else the sandbox cannot withstand any data theft intents from outside the application, and the attacker is able to visit all the data in the memory. The fact is, for many Android devices, root permission can be very easily obtained [XDA Developers 2015a, 2015b]. If a device has been rooted, the */data* partition can be dumped and attacker could restore the data from the remanence without even implementing a physical access to the storage medium.

Erasing the private data is expected to securely erase the files from the file system. We argue that the obscurity in the app data deletion process controlled by Android may cause the leak of sensitive data. An attacker can easily recover all the data remaining on the disk by applying common disk recovery approaches [Wikipedia 2014]. With the help of these recovered data, attackers can implement various attacks such as grabbing sensitive information, obtaining decrypted secret data. In the following, two ethical attacks are performed to verify our analysis.

We have studied two typical obscure file deletion scenarios in which the privacy leak usually happens: (1) app data clearing, and (2) app uninstallation.

3.1.1. Insecure App Data Clearing. The first obscure data deletion operation is Android's Clear Data function for each app. This function is used to reset an app to its initial state and clear an app's privileged data that contains credential information such as browser history, cache, application login token and data encryption keys heavily related to user's privacy. In detail, the Android system uses the `File.delete()` API for app data clearing. This API does not consider the secure data deletion requirement and is insecure in data clearing. We locate the corresponding source code in the Android Open Source Project (AOSP). After checking AOSP source code from 4.0.4 to 6.0.0, we figure out the invoking chain of the `File.delete()` function:

```
initiateClearUserData()->
    ... ->
        clearUserData()->
            do_rm_user_data()->
                    delete_user_data()->
                        delete_dir_contents()->
                            unlinkat()
```

The `File.delete()` interface will invoke the `remove()` function in the Linux C Library, which then invokes `unlink()` and `rmdir()` syscalls for the file deletion operation. Neither of the Linux syscalls does an additional thorough file erasing operation. Therefore, this data clearing process does not meet the demand of secure erasure. While the misunderstanding of security in `File.delete()` misleads users to believe that the privileged data has been thoroughly erased, it results in insecure data deletion operations on the Android system.

3.1.2. Insecure App Uninstallation. Another security concern in obscure file deletion is app uninstallation. The most common security concern for an application on Android is whether the data that it saves on the device is accessible to illegal access. By default, files created on internal storage (more specifically, */data/data/pacakgeName* directory) are accessible only to the owner's app. Because Android implements this isolation, most applications tend to store sensitive data such as a database using internal storage. These sensitive data, if retrieved, can be used to construct a similar context and forge the identity of the app's user.

During the app uninstallation, the Android system will not only remove the app's executable, but also delete all of the corresponding data of the app. Similar to the data-clearing function, the default app uninstallation may also perform insecure data deletion and the private data may still be leaked.

The Android OS performs app uninstallation with a relatively complex operation sequence. We check the latest AOSP source code to confirm if the uninstallation is vulnerable when the system still adopts the insecure data deletion. We found that the app uninstallation triggers `unlinkat()` syscall, which operates in exactly the same way as either `unlink()` or `rmdir()`:

```
deletePackage()->
    deletePackageAsUser()->
        deletePackageX()->
            deletePackageLI()->
                removePackageDataLI()->
                    removeDataDirsLI()->
                        remove()->
                            uninstall()->
                                _delete_dir_contents()
```

Again, this system-level app privacy erasure operation does not consider the risk of insecure data deletion, and is generally vulnerable to any common data recovery–based attack.

3.2. Factory Reset Flaw

Factory reset is a functionality of the Android OS to clean all the metadata from the */data* and */cache* partitions and thus reset the device to its initial state. It is designed to be the last line of defense for data cleansing, taking into account the existing file-deletion method in the underlying file system being incapable. However, due to its capability of flash memory manipulation before booting the Android OS, the *factory reset* operation is not implemented by the Android OS. Instead, it is performed by the device's *Recovery* subsystem. The *Recovery* subsystem is an Android-based lightweight runtime environment parallel to the Android OS. The main functionalities of the *Recovery* subsystem include OTA system updating, factory reset, and so on.

For better user experience or installing other Android distribution versions, end users would like to modify the original *Recovery* subsystem. Currently, the most popular alternative *Recovery* subsystems are CWM [2015] and TWRP [2015]. We have intensively studied both of these *Recovery* subsystems, and found that neither provides a reliable private data erasure mechanism, which means that the *factory reset* cannot thoroughly erase all the data on the flash memory and the SD card (if there is any). The official *Recovery* subsystem makes use of the interface provided by the *ext4_utils* library to wipe the */data* partition; in third-party *Recovery*, such as CWM and TWRP, the *factory reset* command is implemented in its own way. They first parse the */sdcard* partition to check whether it is a virtualized partition part of */data* partition. If so, the *Recovery* subsystem executes the `rm -rf` command on each subdirectory in the */data* partition except for the subdirectory linked to the virtual */sdcard* partition. Note that the file deletion on NAND flash memory is not a reliable data deletion operation. The `rm` deletes only the file index and not the metadata. Therefore, after the *factory reset* operation, the metadata still remain on the */data* partition.

After analyzing the source code of the third-party *Recovery* subsystems CWM and TWRP on five devices, we found that this flaw exists in all the released versions. We further tested devices with CWM and TWRP *Recovery*, and found out that if a device is equipped with an external removable SD card, the vulnerability can be eliminated.

Unfortunately, not only the third-party *Recovery* subsystems are facing the unsafe partition deletion. As we have studied, the original *Recovery* subsystems in Android 4.3 and earlier versions are also suffering from the same vulnerability. The applying of *TRIM* or some other type of partition-clearing implementations are not able to erase the data securely to offer a chance to recover the data from the remanence.

4. EXPERIMENT

4.1. Data Remanence Experiment

To validate our analysis and reveal the potential hazards that may be caused by data-erasing flaws, we perform a series of experiments on mainstream Android devices and observe the data-erasure situation.

4.1.1. Data Clearing. First, we evaluate the data remanence rate after a normal clear-data operation on Android. The experiment is set up on a Sony Lt28h mobile phone with Android 4.1.2. We first select 100 files of various types in an app's privileged sandbox environment, then perform a clear-data operation to erase those files on the internal storage of the Sony Lt28h. After the clearing, the raw memory image of the internal storage is dumped to perform common file recovering for the 100 chosen files, and the file recovering rate is calculated. We repeat this deletion operation three times with different files of different apps. The results are shown in Table II. As the results show, if the privileged data is only cleared by the clear-data operation, it is actually not effectively erased at all.

Table II. Data Remaining After Clear-Data Operation on Sony Lt28H

File Set Size	Data Remanence Rate
85.64MB	100%
150.63MB	100%
400.30MB	100%

Table III. Data Remanence Rate After App Uninstallation on Sony Lt28h

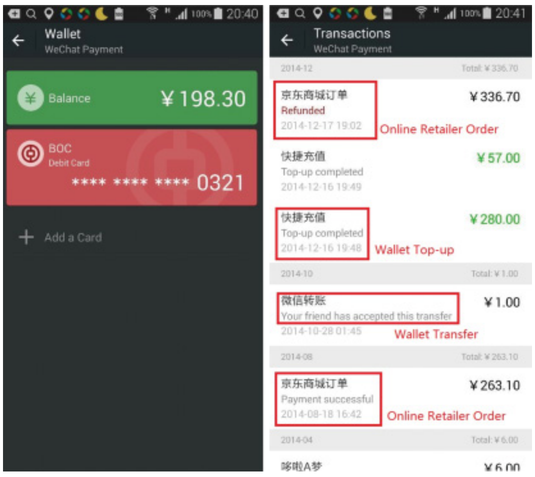
Exp	WeChat	QQ	Microblog	Facebook	Snapchat	All
#1	86/110	184/190	64/79	65/70	23/25	313/399
#2	79/79	160/160	73/78	66/70	13/15	358/426
#3	80/80	149/156	40/69	66/70	15/15	334/396

The second experiment that we performed uses a Galaxy Nexus 4 mobile phone with Android 4.4.2, which belongs to one of our colleagues for daily use. As this device is usually used as a mobile terminal to browse web pages with Chrome, the owner has already cleared the relevant data to protect his privacy before contributing this device to our experiment. We first dump the raw disk image of this device's internal storage, then we use state-of-the-art data recovering tools such as *Recuva*, *Extundelete*, and *UFS explorer* to extract as many files as we can. With the help of a normal Chrome application on another Android device as a template, we could pick up those files belonging to Chrome from the recovered files. Finally, 275 files of Chrome are picked up and some manual analyses are employed to extract a large number of private data, such as browsed images, videos, browsing history, and cookies.

In conclusion, due to the obscurity of the data-clearing function of Android, the insecure data deletion operation does not protect the owner of the device from avoiding private data leakage, which may jeopardize the device owner seriously in real life.

4.1.2. App Uninstallation. To evaluate app uninstallation vulnerability, we perform common app uninstallation procedures on an Android device and observe the data-erasure situation. We evaluate app uninstallation vulnerability using two devices. The first device that we choose is a Sony Lt28h mobile phone with Android 4.1.2 (without the TRIM feature). We would like to quantitatively evaluate the data remanence rate of app uninstallation when a normal app uninstallation operation is performed. We choose five typical Android apps to test, including *WeChat*, *QQ*, *MicroBlog*, *FaceBook*, and *SnapChat*. For each app, we first install it and use it for a while. Then, we record every file in the app's internal storage directory. Finally, we uninstall the app, reboot the operating system, then retrieve the raw disk image of the internal */data* partition. After acquiring the raw disk image, we conduct a common file-recovery approach to extract as many files as possible, and calculate the file-recovery rate. For each app, we repeat the experiment three times. We also perform one test operating five apps concurrently. The results are shown in Table III. As the results show, almost 80% of the data still remains.

The second device that we choose is a Samsung Galaxy S5 mobile phone with Android 4.4.2 with TRIM feature enabled. The tested device is from a common user and is in use for a long time. Before testing, all of the apps on this device are uninstalled. We perform the same attack on this mobile phone and find that, even with the TRIM feature activated, the dumped raw disk image of */data* partition still contains a huge amount of sensitive data. In particular, we aim at attacking the *WeChat* app, which is a very popular app in mainland China, with more than four hundred million users, supporting not only online communication but also an online payment service on this device. From the dumped raw disk image, we recover 1214 files from


20:40
Wallet
WeChat Payment
Balance ¥198.30
BOC
Debit Card
**** **** **** 0321
Add a Card

20:41
Transactions
WeChat Payment
2014-12 Total: ¥336.70
京东商城订单
Refunded
2014-12-17 19:02
¥336.70
快捷充值
Top-up completed
2014-12-16 19:49
¥57.00
快捷充值
Top-up completed
2014-12-16 19:48
¥280.00
2014-10 Total: ¥1.00
微信转账
Your friend has accepted this transfer
2014-10-28 01:45
¥1.00
2014-08 Total: ¥263.10
京东商城订单
Payment successful
2014-08-18 16:42
¥263.10
2014-04 Total: ¥6.00
哆啦A梦
¥6.00

Fig. 2. Attack on WeChat app.

the */data/data/com.tencent.mm* directory. These data are crucial, as both identify the authentication token and message database. We transfer these data to another device with a *WeChat* app just installed and successfully forge the identify of the original user. As Figure 2 shows, not only can an attacker retrieve the chat record and friends list information, but an attacker can also observe the online transaction information of the app.

4.1.3. Factory Reset. Data remaining after *factory reset* is a widely existing threat for the two most prevailing third-party *Recovery* subsystems, and once attackers try to retrieve data from any secondhand device, over 90% of the data blocks will be recovered for the next-step data content understanding. Given the metadata erasing flaw, it is not difficult to construct a privacy retrieving attack. We test the metadata recovery attack on five mainstream Android devices, including Nexus4, Nexus7, Galaxy S3, Motorola MT917, and Sony Lt28h. Our experiment is conducted with the CWM and TWRP *Recovery* subsystems. For each device-*Recovery* combination, three flash memory images are dumped:

—the entire */data* partition's image, denoted as $Image_o$,
—the after third-party-*Recovery factory reset* image, denoted as $Image_w$, and
—after *Reset*, when the OS initiates the partition, the third image is obtained as $Image_i$.

We developed a different tool to observe the change of the data blocks in $Image_w$ and $Image_i$ by comparing with $Image_o$. The results are listed in Table IV.

4.2. Deletion Latency on Android

Although we have discussed the flaws and root causes of file-delete operations on Android, we also want to investigate how long the data remanence will exist. To further determine the remanence period of improper deleted data, we conduct a long-term experiment on deletion latency, which reflects the period between data deletion and its actual removal from the storage medium. If the deletion latency can be ignored (e.g., several hours), deleted private data can be expected to be secure for the lack of attack surface. However, if the deletion latency is long enough, the chance for the attacker to retrieve the data is not negligible.

Table IV. Data Remaining After Data Wiping (in $Image_w$) and After Reboot (in $Image_w$) for Various Devices

Device	Recovery version	Partition size (Number of Blocks)	SqLite block count	Image_w	Image_i
ASUS Nexus 7 (Android 4.4.2)	TWRP 2.6.3.1	6.01GB(1575680)	3714	92.55%	97.10%
	CWM 6.0.4.3		2524	99.95%	99.14%
Samsung Galaxy S3 (Android 4.2.2)	TWRP 2.7.0.0	11.5GB(3022848)	8915	99.83%	99.13%
	CWM 6.0.4.6		973	99.97%	99.73%
Sony Lt28H (Android 4.4.2)	TWRP 2.6.3.0	2.00GB(524288)	2904	0.48%	8.69%
	CWM 6.0.3.0		5168	0%	0.49%
Motorola MT917 (Android 4.1.2)	CWM 5.0.2.5	3.84GB(1007616)	2195	13.7%	14.88%
LG Nexus 4 (Android 4.4.2)	TWRP 2.6.3.3	13.1GB(3449600)	11227	99.74%	97.49%
	CWM 6.0.4.7		11476	99.9%	98.34%

Note: TWRP does not support MT917.

Table V. Device and File Set Information Regarding Deletion Latency Experiment

Device (Android Version)	Disk Size (Free/All)	File set size	Amount of files (blocks)	Maximal/Minimum file size
Huawei Honor 4A (5.1.0)	2.5GB/8GB	42.4MB	222(10710)	25140KB/4KB
Nexus4 (4.4.2)	10.5GB/16GB	36.2MB	743(9119)	6370KB/4KB
Nexus5 (5.0.0)	4.1GB/16GB	57.5MB	336(14705)	8346KB/4KB

To measure the deletion latency of deleted data exposed to attackers, our experiment records the actual data removal period of several apps' private data on different Android devices. We choose three mainstream Android devices (Huawei Honor 4A, LG Nexus4, and LG Nexus5) as our experimental targets; these experimental devices are sent to different testers for daily use. The information regarding devices and target files is listed in Table V. All three devices contain a monitoring program that records the occurrence of exact data removal events. Through more than 2mo of testing, how data remanence changes is summarized.

The first step of our experiment is to label the deleted files' location so that later monitoring could be employed. Before deleting all the target files through common Android file deletion API, we directly read and record the block id and block data of each file. Then, we execute the delete operation to lead all the target blocks marked as unused by the file system. Among the unused blocks, about one-third are adjacent, while others are individually distributed on the disk. This distribution is an important feature because the size of unused disk fragments will influence the file system's recycling, which is demonstrated in our testing, as follows.

We install a monitoring program with root privilege on each device to record the changing of data remanence. After the deletion operations, the monitoring program start to continuously scan all target blocks every hour, checking whether a block has been actually overwritten and recording the remanence rate of all deleted data. Once the monitoring program starts running, three devices are delivered to different volunteers for daily use. All volunteers are not aware of the details of the experiment to keep their cellphone usage habits over the entire period of the experiment. After 2mo, we reclaim the experiment devices and analyze the log of the monitoring program to reach the final conclusions.

Figure 3 shows our experimental results, which reflect the relationship between data remanence rate and time. We can see at a glance that, during the experiment, the data remanence rate is continuously decreasing. However, even after 2mo of daily operations, none of the three experiment devices has entirely wiped the target deleted

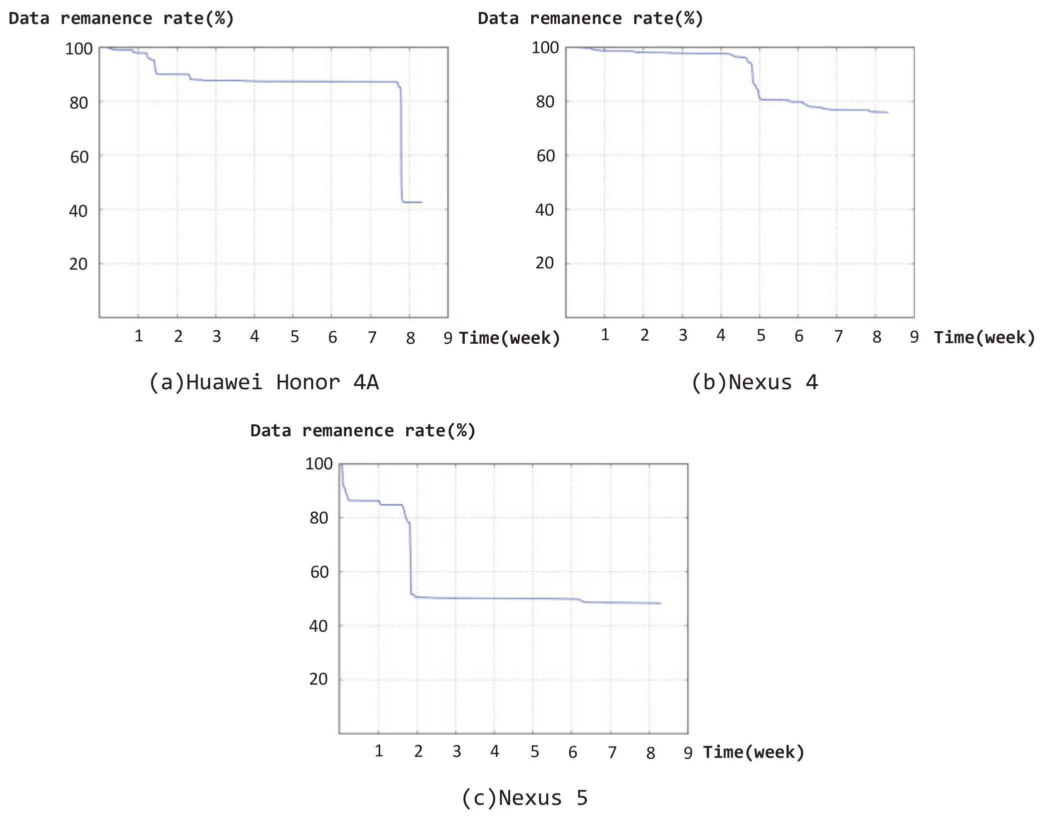


Fig. 3. Data remanence rate of deleted files.

data. At least 40% of the target deleted data still remains on each of the three devices. Particularly, the tested Nexus 4 smartphone reveals an approximate 90% data remanence, which leads to a great possibility of data leakage. After a thorough analysis of the log data, many other observations are made. First, individual unused blocks are reused prior to adjacent unused blocks. According to the block allocation algorithm of the *ext4* file system, which follows a greedy strategy, the most suitable unused area is always chosen for writing new data. For the Android system, small files such as web browser logs, temporary records, and configuration files are more likely to be created or modified during daily use. The operations on small files will cause the reallocation of unused small-sized fragments; thus, the individual unused blocks are more likely to be recycled. Second, we note that there are some significant declines in data remanence rate during the experiment. These declines imply the allocation of some large unused areas with adjacent unused blocks. We find that it is unusual for daily use to trigger the allocation of a large file written on Android, as we only observe a few such events. Thus, data in adjacent unused blocks are expected to stay longer than those in individual unused blocks.

Another important conclusion drawn from our experiment is that there is no remarkable relationship between deletion latency and disk size, although prior research [Reardon et al. 2012] shows that the deletion latency of a log-structured file system has a positive correlation with disk size in simulation experiments. But, according to Figure 3, the disk size of Nexus5 is larger than Huawei Honor 4A, while the deletion latency of Nexus5 is obviously shorter than Huawei Honor 4A. In our experiment, we find that the actual deletion latency mainly depends on user behavior and disk block distribution.

4.3. Recovering from Incomplete Data Fragments

In the previous sections, we used normal file/data-recovery utilities such as *dd*, *recuva*, or *extundelete* to recover deleted files. The integrity of deleted data and file system metadata (e.g., journal) is mandatory for normal data-recovery utilities. However, the result of deletion latency experiment shows that such integrity may be broken after being used for a long time. In this context, a significant amount of valuable data still remains in the incomplete data fragments.

To assess the data-remain issue in this situation, we implemented *DataRaider*, which adopts a *file-carving* technique to recovery files from crumbs. It is implemented as an automated sensitive information–recovering framework for evaluating data remains when the integrity of remaining data is broken.

File carving is a useful technique for recovering specific types of files from data fragments. Here, we choose an SQLite Database file as our target because Android suggests that app uses SQLite database to store data that are frequently queried. Most of the confidential data in Android are managed with SQLite3 DBMS and are stored as a *.db* file in the userdata partition, according to the Android development document's recommendation. Typical databases for system applications include short message (mmssms.db), contacts information (contacts2.db), system setting (settings.db), keychain (grants.db), and schedule (calendar.db). Except for the standard system apps, a huge amount of third-party apps also store their data using the SQLite interface.

As the target of *DataRaider* is to recover deleted files from the wiped devices, its recovery process focuses on reconstructing the SQLite database on the *userdata* partition. The entire recovery process is shown in Figure 4.

While common ext4 data-recovery techniques often rely on the journaling feature to boost the data recovery [Kim et al. 2012], we aim at recovering remaining data without any support from the file system.

DataRaider starts with an disk image file. It is split into data blocks first and analyzes the data blocks directly.

First, it extracts data blocks from the /userdata partition. We investigated more than 20 devices, and found that all of them adopt a 4KiB block size for the ext4 file system's choice. Moreover, we also find that more than 95% of the SQLite databases adopt the page size as the same as the ext4 block size. Thus, the splitting of the raw disk image separates the entire data into units of 4KiB.

Second, *DataRaider* discriminates every block to filter out potential SQLite pages. A typical SQLite3 database file consists of multiple pages. The size of one page is defined in the database file's header. Generally, SQLite on Android uses a 4KB sized page corresponding to the ext4 file system's default block size. The page number starts from 1 and continues in one database file. The first page is the SQLite3 header page, which is crucial for a database file, because it contains the header and the master table *sqlite_master* of this database. Except for the header page, a SQLite database can also contain other types of pages, among which is the one we are interested in: the *b-tree* page. SQLite DBMS uses the *b-tree* page to store the meta structure and data content. A SQLite3 database can be approximately seen as a tree whose root is the header page, and most of its child nodes and leaf nodes are the *b-tree* page [SQLite 2015]. The identification of the SQLite3 data page relies on the internal structure of the SQLite3 b-tree page. A SQLite3 b-tree page stores one or multiple data records of the database. Ideally, the file will be allocated consecutive blocks [Kim and Kim 2012]. This causes

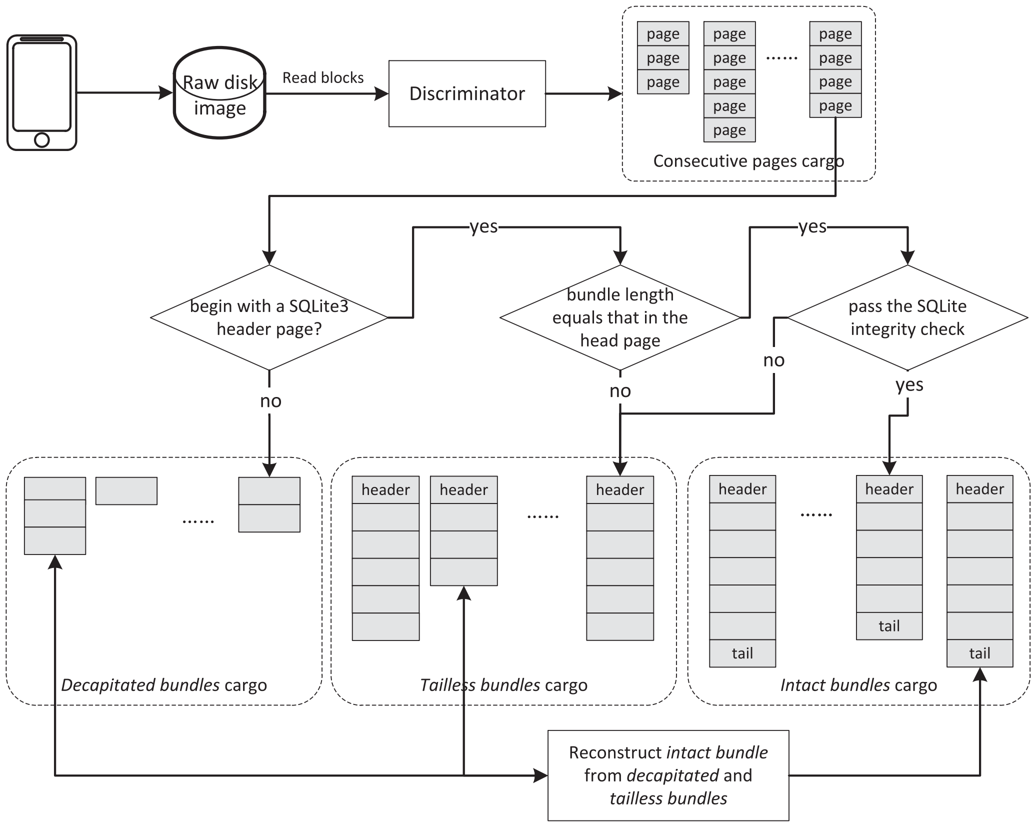

Raw disk image
Read blocks
Discriminator
page
Consecutive pages cargo
yes
begin with a SQLite3 header page?
bundle length equals that in the head page
pass the SQLite integrity check
no
yes
header
tail
Decapitated bundles cargo
Tailless bundles cargo
Intact bundles cargo
Reconstruct intact bundle from decapitated and tailless bundles

Fig. 4. Sensitive information extraction process.

data blocks of the same file to be close together. We'll use this fact to restrict where we search for deleted data. Then our discriminator will group one or multiple consecutive pages as a *bundle*. It will continually analyze the block until meeting a block that does not meet the rule. After this process, *DataRaider* stores the bundles in a *cargo* for further file reconstruction.

The last step is to perform an SQLite database reconstruction procedure to recover sensitive information as much as possible. For bundles in the *bundle cargo*, *DataRaider* categorizes them as three types: intact bundle, tailless bundle, and headless bundle. Intact bundle denotes a group of consecutive blocks that is already a complete database file. Tailless bundle is a group of consecutive blocks that contains an SQLite3 header page but is not an intact database. Headless bundle denotes a group of consecutive data pages. In the recovery process, now that an intact bundle is already a recovered database, the reconstruction of a database mainly tries to fix a tailless bundle with a header page to an intact database. According to the header page contained in a tailless bundle, *DataRaider* could determine the original size of the database and calculate the size of the lacked part (we denote the size as L). Then, it tries to supplement one tailless bundle with other headless bundles. *DataRaider* searches for a set of headless bundles with the total size equal to L, and tries to combine those bundles with the tailless bundle, then verifies whether it is a valid database file. This process is iteratively employed until every headless bundle is tested.

Table VI. Recovered Data Proportion of Sensitive Information Related Database on Various Devices

Device	Database	Origin Size	Data Recovered
Nexus4	SMS	428KB	2.8%
	Contact	1184KB	84%
	KeyChain	20KB	100%
	System Setting	88KB	100%
	Calendar	164KB	7.3%
	3rd APP (WeChat)	1112KB	100%
Galaxy S3	SMS	292KB	62%
	Contact	1024KB	72%
	KeyChain	20KB	100%
	System Setting	140KB	100%
	Calendar	388KB	47%
Nexus 7	Contact	904KB	39.8%
	KeyChain	20KB	100%
	System Setting	76KB	15.8%
	Calendar	160KB	77%

We evaluate the functionality of *DataRaider* on three Android devices (Nexus4, Galaxy S3, and Nexus 7). We try to restore the database of SMS, contact list, keychain, system setting, and more. After a *factory reset* operation, we use the devices for several days. Then, we put those devices into the recovery test. The results are listed in Table VI. Except for very few entries, almost all private information has been successfully restored by performing sophisticated data retrieval to a certain extent. This experiment reveals that a lot of extractable sensitive data has been left on the disk while some data blocks were missing and the integrity of data was compromised.

We evaluate the performance of *DataRaider* by comparing the time cost with a well-known stream file-carving tool *Foremost* [SourceForge 2015].

Foremost is one of the first file carvers that implements a sequential header to footer file carving by the file's header and its size. Carving SQLite database files is difficult for common file-carving tools because of the missing footer and the size of the file. To provide a better solution, *DataRaider* adopts a customized file reconstruction stage right after discriminating related blocks from the disk image. Despite more time cost, this stage makes *DataRaider* competent to recover the SQLite database files.

We divide the whole recovery process into two stages for *DataRaider*, discrimination and reconstruction. In our experiment, *Foremost* has been applied to carve the common application file types (e.g., pdf, jpg, png, bmp, mp3) from the given disk images. It does not write any detected files back to the disk. *DataRaider* is used for carving SQLite database files without writing reconstructed files back to the disk. The experiment is implemented on a PC with Intel i3-2120 and 16GB RAM. Both *DataRaider* and *Foremost* are used to analyze a 2GB disk image 10 times.

On average, the results show that the discrimination stage of *DataRaider* cost 65.06s and the reconstruction stage cost 42.54s, and it has successfully recovered 243 SQLite database files. *Foremost* cannot recover SQLite database files. Instead, it costs 60.37s to recover 444 common application files.

The recovery process for *Foremost* and the discrimination stage of *DataRaider* have cost equivalent time. The need for both of them to parse the whole disk image cannot be neglected. The next stage for *DataRaider* consumes some extra time on reconstructing the SQLite database files, which is in an acceptable range considering the extra functionality it provides over *Foremost*.

Our experiment shows that the overall performance of *DataRaider* is comparable with mainstream file-carving tools.

5. MITIGATION

As an open platform, the Android system has various inevitable implementations. The fragmentation of Android systems has ignited discussions on many security topics. One is the vulnerable data wiping in the Android system. As its various causes among myriad versions, there has been difficulty in finding an all-in-one solution for secure data clearing. The battle between data clearing and recovery will continue.

Various techniques have been developed to resist recovery attacks. The widely known methods include overwriting-based secure deletion, data encryption, and physical destruction of the device. In this article, we only focus on software-assistant data deletion.

Studies claim that with the *TRIM* feature, the Android OS can issue *TRIM* commands to wipe the entire drive in seconds [King and Vidas 2011]. Another aspect of study focuses on secure deletion, which has been studied in a variety of contexts and has also been extensively surveyed [Wei et al. 2011; Reardon et al. 2012, 2013]. Secure deletion is the basis of private data erasure, but unfortunately is very hard to implement correctly on most mobile devices. Wei et al. [2011] empirically evaluate the effectiveness of erasing data from flash-based SSDs. Their conclusion is that none of the available software techniques for sanitizing individual files was effective, although the proposed attack requires laboratory data recovery techniques and equipment. Moreover, Reardon et al. [2012] thoroughly discussed secure deletion at the user level. They propose two user-level solutions that have achieved secure deletion. Leom et al. [2016] conducted a comparative summary of existing approaches to realize secure flash storage deletion and identified existing limitations with experiments.

We support the idea of data encryption as an efficient protection strategy. When the encrypted data is about to be deleted, securely disposing of the encrypted key rather than wiping the data is easier to achieve than an equally secure deletion. However, achieving a robust and efficient encryption scheme may involve many issues, including performance overhead and key management, for example, the Android's Full Disk Encryption (FDE) scheme. Although it has kept evolving since Android 3.0, it still has been restricted by many user-level applicability and compatibility factors; the security bound is thus reduced. We will detail the flaws of FDE in Section 6.

Lee et al. [2008] has designed a NAND flash file system with a secure deletion functionality. This method uses the idea of encryption. It requests that all the keys of a specific file be stored on the same block. Therefore, only one erasing operation on the key files is required to securely delete the data files. However, their work supports only the YAFFS file system, yet current Android devices generally adopt the ext4 file system. Wang et al. [2012] present a FUSE (Filesystem in USErspace) encryption file system for Android. The proposed encrypted file system introduces about 20 times performance overhead than the normal system.

The trusted SQLite database storage [Luo et al. 2013] is another option when performance is a major concern, although we have to remember that the lightweight SQLite database encryption solution is less secure than full-disk encryption. At the system-booting phase, it is faster to load an encrypted database than an encrypted partition. Also, these sensitive files are decrypted on-the-fly only when legitimate users are unlocking and using the phone. In addition, to reload the encrypted database is of little cost, thus each time the screen is locked, the system could erase decrypted data in memory directly and no sensitive data is stored. This means that even if the attacker has direct access to the remaining data, the attacker still cannot get any useful data. Thus, the sensitive files are well protected.

Another possible mitigation can be an application-level security enhancement. One of the implementations can be hooking the key libC functions related to disk I/O. Wrapped by some cryptographic operations, the data writes to the disk in cipher text form. It would be satisfying for both security and efficiency purposes.

Given the present situation of Android OS fragmentation, this method provides transparent encryption that adapts to almost all Android versions without interrupting the device user. Compared to system modification schemes or upgrading the OS to a higher version, such as Android Jelly Bean or Lollipop, a more realistic solution users would prefer is a simple way to deploy security enhancement on their applications.

6. RELATED WORK

6.1. Data Recovery

Many data-recovery methods designed for PCs have been applied on mobile devices, such as file recovery and file carving [Kim et al. 2012; SourceForge 2013; Piriform 2015]. While the ext4 file system provides many improved features, one of its features, journaling, can be leveraged to boost data recovery. Journaling is a technique employed by many file systems in crash recovery situations. Tools such as *extundelete* can recover files immediately after parsing the ext4 file system's journal, usually within a few minutes. The contents of an inode can be recovered by searching the file system's journal for an old copy of that inode. Then, that information can be used to determine the file's location within the file system [Fairbanks et al. 2010].

JDForensic [Kim et al. 2012] is a tool aiming to analyze the journal log area in ext4 file systems and extract journal log data to recover deleted data and analyze user actions. Extundelete [SourceForge 2013] is another popular open-source tool focusing on recovering files from a disk with ext3 and ext4 file systems. It is able to recover the contents of an inode by searching the file system's journal for an old copy of that inode. However, if the supporting journal information is broken or missing, both tools are not able to recover any files.

Close to our research, there are many studies focusing on direct data recovery using both forensics and physical access. Our work is generally based on these studies, but we focus on data-erasure failure and related concrete threats rather than data remanence and extraction. A direct approach to data extraction is to read the internal memory through the boundary-scan (JTAG) test pins. Breeuwsma et al. [2006] introduce the details of using a JTAG test access port to access memory chips directly. This approach is feasible for when a phone is locked and cannot be accessed via USB cable. The disadvantage is that the mobile device needs to be disassembled, which requires specific analyzing equipment and knowledge to achieve.

Another acquisition of Android memory images proposed by FROST [Müller and Spreitzenbarth 2013] is against full disk encryption. It focuses on breaking disk encryption of Galaxy Nexus devices. Again, it requires a complicated experimental environment to carry out the attack.

There are also studies aimed at specific resources on Android. Do et al. [2015] propose an adversary model to facilitate forensic investigations of mobile devices. An evidence collection and analysis methodology for Android devices is provided in this article. With the help of this methodology, Do and Choo extract information of forensic interest in both the external and internal storage of six chosen mobile devices.

Leom et al. [2015] provide a study of thumbnail recovery in Android. They examine and describe the various thumbnail sources in Android devices and propose a methodology for thumbnail collection and analysis from Android devices.

Immanuel et al. [2015] study the diversity of cache formats on Android and provide a taxonomy of them based on app usage. Using this taxonomy as a base, they propose a systematic process, known as the Android Cache Forensic Process, to forensically classify, extract, and analyze Android caches.

6.2. FDE Flaw

Since Android 3.0, Google has provided *full-disk encryption (FDE)* as an optional security service. FDE derives from the *dm-crypt* feature in Linux. The user can choose to activate the FDE service from the system settings.

Since the Android OS version 5.0 (Lollipop), the full-disk encryption mechanism has been improved to counter brute-force attacks and has enabled full crypto features by default. Being similar to iOS, it adopts hardware-assist encryption and implements per-app encryption as well. Google has claimed that Lollipop would introduce hardware support to enhance security strength and boost cryptographic process speed.

However, a weaker full-disk encryption is still prevalent in Android app markets, which would lead to easy recovery of the data. The early versions, such as Jelly Bean (versions 4.1–4.3.1) and Kitkat (versions 4.4–4.4.4) are still in use. Until May 2014, Android Jelly Bean was still the dominant OS version in the Android ecosystem. Android Jelly Bean provides a weaker full-disk encryption that would make brute-force attack on the encryption keys much easier [Elenkov 2014].

First, due to the lack of the hardware encryption chip's support, the master key for FDE is generated from the Android lockscreen passcode. The encryption parameters for calculating the secret keys are stored on a special structure in a disk partition called the *crypto footer*. Before Android 5.0, the attacker is capable of launching a brute-force attack against the PIN by analyzing the specific information in the structure to obtain the encryption key. If the encryption key is acquired, data remanence is again the source of private data leaking. According to disk encryption [Elenkov 2014], for the FDE scheme before Android 4.4, the popular brute-force attacking tool *hashcat* can achieve more than 20,000 PBKDF2 hashes per second on a notebook with NVIDIA GeForce 730M, and recovers a 6-digit PIN in less than 10s. On the same hardware, a 6-letter (lowercase only) password takes about 4h. Considering the custom of users (less people would like to set a complex lockscreen passcode and repeatedly input it every time), recovering the master key of FDE in a reasonable time is quite possible. For Android 4.4.x, the complexity of brute-force attack is increased, but still feasible. This simply restricts the attacker to recovering a passcode in a relative longer time period.

Second, postulating the using of a third-party *Recovery* subsystem, FDE would face an even worse situation. As we have deliberated in the previous sections, the ineffective implementation `rm` command in some *Recovery* systems has caused the inability to wipe the data content on the disk. In this case, the encrypted metadata have been kept intact. With the help of the encryption key retrieving attack, the complete content on the disk can be revealed.

In a word, the FDE scheme before Android 5.0 is not as effective as expected. A more robust data protection requires a better encryption scheme to thoroughly eliminate the threat of data remanence.

7. CONCLUSIONS

In this work, we analyze several defects in the Android system, such as data remaining after data clearing, app uninstallation, and even *factory reset*. To prevent private data leak caused by recovering the data remaining, three aspects of data erasure must be implemented: generic file deletion, app uninstallation, and metadata erasure. Due to various reasons, private data erasure fails in many ways. We perform a systematic study on the impact of imperfect data erasure operations, and demonstrate how the attackers manage to recover sensitive information in three scenarios: generic file deletion, app uninstallation and factory reset. Essentially, the primary cause of erasure failure is the inefficient implementation on file operations and the third-party *Recovery* system implementation flaws.

As do other successful operating systems, Android provides agility and convenience to smartphone users, but its software designers should consider more security enhancement at the design phase. Confidential information exists in the Android system as generic files, information residing in an app, or metadata on flash memory. In this work, we exhibit how it has been ignored and has caused serious data remanence in Android systems. Data wiping is more important in the mobile environment than in the traditional computing context. In addition to hardware-assist security enhancement such as TrustZone, we hope to propose some OS-level data wiping or protection mechanism for the Android ecosystem in the future.

REFERENCES

Steven Arzt, Siegfried Rasthofer, Christian Fritz, Eric Bodden, Alexandre Bartel, Jacques Klein, Yves Le Traon, Damien Octeau, and Patrick McDaniel. 2014. FlowDroid: Precise context, flow, field, object-sensitive and lifecycle-aware taint analysis for Android apps. In *Proceedings of the 35th ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI'14)*. ACM, New York, NY, 259–269. DOI:http://dx.doi.org/10.1145/2594291.2594299

Abdullah Azfar, Kim-Kwang Raymond Choo, and Lin Liu. 2015. Forensic taxonomy of popular Android mHealth apps. *arXiv preprint arXiv:1505.02905* (2015).

Abdullah Azfar, Kim-Kwang Raymond Choo, and Lin Liu. 2016a. An Android communication app forensic taxonomy. *Journal of Forensic Sciences* 61, 5, 1337–1350.

Abdullah Azfar, Kim-Kwang Raymond Choo, and Lin Liu. 2016b. Android mobile VoIP apps: A survey and examination of their security and privacy. *Electronic Commerce Research* 16, 1, 73–111.

Michael Backes, Sebastian Gerling, Christian Hammer, Matteo Maffei, and Philipp von Styp-Rekowsky. 2013. AppGuard: Enforcing user requirements on Android apps. In *Proceedings of the 19th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS'13)*. Springer, Berlin, 543–548. DOI:http://dx.doi.org/10.1007/978-3-642-36742-7_39

Steven Bauer and Nissanka Bodhi Priyantha. 2001. Secure data deletion for Linux file systems. In *Usenix Security Symposium*, Vol. 174.

Graeme B. Bell and Richard Boddington. 2010. Solid state drives: The beginning of the end for current practice in digital forensic recovery? *Journal of Digital Forensics, Security and Law* 5, 3, 1–20.

Ing Breeuwsma and others. 2006. Forensic imaging of embedded systems using JTAG (boundary-scan). *Digital Investigation* 3, 1, 32–42.

Sven Bugiel, Stephan Heuser, and Ahmad-Reza Sadeghi. 2013. Flexible and fine-grained mandatory access control on Android for diverse security and privacy policies. In *Usenix Security*. 131–146.

CWM. 2015. ClockworkMod Recovery. Retrieved December 6, 2016 from https://www.clockworkmod.com.

Quang Do, Ben Martini, and Kim-Kwang Raymond Choo. 2015. A forensically sound adversary model for mobile devices. *PloS One* 10, 9, e0138449.

Nikolay Elenkov. 2014. Revisiting Android disk encryption. http://nelenkov.blogspot.com/2014/10/revisiting-android-disk-encryption.html. (2014).

William Enck, Peter Gilbert, Seungyeop Han, Vasant Tendulkar, Byung-Gon Chun, Landon P. Cox, Jaeyeon Jung, Patrick McDaniel, and Anmol N. Sheth. 2014. TaintDroid: An information-flow tracking system for realtime privacy monitoring on smartphones. *ACM Transactions on Computer Systems* 32, 2, Article 5, 29 pages. DOI:http://dx.doi.org/10.1145/2619091

Ext4 Wiki. 2015. Ext4 and Ext2/Ext3) Wiki. Retrieved December 6, 2016 from https://ext4.wiki.kernel.org/index.php/Main_Page.

Kevin D. Fairbanks, Christopher P. Lee, and Henry L. Owen III. 2010. Forensic implications of EXT4. In *Proceedings of the 6th Annual Workshop on Cyber Security and Information Intelligence Research*. ACM, 22.

ForensicsWiki. 2014. Solid State Driver Forensics. Retrieved December 6, 2016 from http://www.forensicswiki.org/wiki/Solid_State_Drive_(SSD)_Forensics.

Stephan Heuser, Adwait Nadkarni, William Enck, and Ahmad-Reza Sadeghi. 2014. ASM: A programmable interface for extending Android security. In *Proceedings of the 23rd USENIX Conference on Security Symposium (SEC'14)*. USENIX Association, Berkeley, CA, 1005–1019. http://dl.acm.org/citation.cfm?id=2671225.2671289

Felix Immanuel, Ben Martini, and Kim-Kwang Raymond Choo. 2015. Android cache taxonomy and forensic process. In *IEEE Trustcom/BigDataSE/ISPA,* Vol. 1. IEEE, 1094–1101.

JEDEC. 2014. Flash Memory. Retrieved from http://www.jedec.org/category/technology-focus-area/flash-memory-ssds-ufs-emmc.

Jinseong Jeon, Kristopher K. Micinski, Jeffrey A. Vaughan, Ari Fogel, Nikhilesh Reddy, Jeffrey S. Foster, and Todd Millstein. 2012. Dr. Android and Mr. Hide: Fine-grained permissions in Android applications. In *Proceedings of the 2nd ACM Workshop on Security and Privacy in Smartphones and Mobile Devices*. ACM, 3–14.

Dohyun Kim, Jungheum Park, Keun-gi Lee, and Sangjin Lee. 2012. Forensic analysis of Android phone using Ext4 file system journal log. In *Future Information Technology, Application, and Service*. Springer, 435–446.

Hyeong-Jun Kim and Jin-Soo Kim. 2012. Tuning the Ext4 filesystem performance for Android-based smartphones. In *Frontiers in Computer Education*. Springer, 745–752.

Christopher King and Timothy Vidas. 2011. Empirical analysis of solid state disk data retention when used with contemporary operating systems. *Digital Investigation* 8, S111–S117.

Kenneth C. Kung. 1993. Secure file erasure. (Nov. 23 1993). US Patent 5,265,159.

Jaeheung Lee, Junyoung Heo, Yookun Cho, Jiman Hong, and Sung Y. Shin. 2008. Secure deletion for NAND flash file system. In *Proceedings of the 2008 ACM Symposium on Applied Computing*. ACM, 1710–1714.

Ming Di Leom, Kim-Kwang Raymond Choo, and Ray Hunt. 2016. Remote wiping and secure deletion on mobile devices: A review. *Journal of Forensic Sciences* 61, 6, 1473–1492.

Ming Di Leom, Christian Javier DOrazio, Gaye Deegan, and Kim-Kwang Raymond Choo. 2015. Forensic collection and analysis of thumbnails in Android. In *IEEE Trustcom/BigDataSE/ISPA,* Vol. 1. IEEE, 1059–1066.

Yuhao Luo, Dawu Gu, and Juanru Li. 2013. Toward active and efficient privacy protection for Android. In *Proceedings of the International Conference on Information Science and Technology (ICIST'13)*. IEEE, 924–929.

Tilo Müller and Michael Spreitzenbarth. 2013. FROST. In *Applied Cryptography and Network Security*. Springer, 373–388.

Piriform. 2015. Recuva. Retrieved December 6, 2016 from https://www.piriform.com/recuva.

Hal Pomeranz. 2010. Understanding ext4. Retrieved from http://digital-forensics.sans.org/blog/2010/12/20/digital-forensics-understanding-ext4-part-1-extents.

Darren Quick and Kim-Kwang Raymond Choo. 2013a. Digital droplets: Microsoft SkyDrive forensic data remnants. *Future Generation Computer Systems* 29, 6, 1378–1394.

Darren Quick and Kim-Kwang Raymond Choo. 2013b. Forensic collection of cloud storage data: Does the act of collection result in changes to the data or its metadata? *Digital Investigation* 10, 3, 266–277.

Joel Reardon, David Basin, and Srdjan Capkun. 2013. Sok: Secure data deletion. In *Proceedings of the IEEE Symposium on Security and Privacy (SP'13)*. IEEE, 301–315.

Joel Reardon, Claudio Marforio, Srdjan Capkun, and David Basin. 2012. User-level secure deletion on log-structured file systems. In *Proceedings of the 7th ACM Symposium on Information, Computer and Communications Security*. ACM, 63–64.

SourceForge. 2013. extundelete. Retrieved December 6, 2016 from http://extundelete.sourceforge.net/.

SourceForge. 2015. Foremost. Retrieved December 6, 2016 from http://foremost.sourceforge.net/. (2015).

SQLite. 2015. SQLite3 File Format. Retrieved December 6, 2016 from https://www.sqlite.org/fileformat.html.

TWRP. 2015. Team Win Recovery Project. Retrieved December 6, 2016 from http://teamw.in/project/twrp2. (2015).

Zhaohui Wang, Rahul Murmuria, and Angelos Stavrou. 2012. Implementing and optimizing an encryption filesystem on Android. In *Proceedings of the IEEE 13th International Conference on Mobile Data Management (MDM'12)*. IEEE, 52–62.

Michael Wei, Laura M. Grupp, Frederick E. Spada, and Steven Swanson. 2011. Reliably erasing data from flash-based solid state drives. In *Proceedings of the 9th USENIX Conference on File and Storage Technologies (FAST'11)*. USENIX Association, Berkeley, CA, 8–8. http://dl.acm.org/citation.cfm?id=1960475.1960483

Wikipedia. 2014. Flash Memory: SSDs, UFS, e.MMC. Retrieved December 6, 2016 from http://en.wikipedia.org/w/index.php?title=Flash_memory.

Chiachih Wu, Yajin Zhou, Kunal Patel, Zhenkai Liang, and Xuxian Jiang. 2014. AirBag: Boosting smartphone resistance to malware infection. In *Proceedings of the 21st Annual Network and Distributed System Security Symposium (NDSS'14)*. Retrieved from http://www.internetsociety.org/doc/airbag-boosting-smartphone-resistance-malware-infection.

XDA Developers. 2015a. Rooting. Retrieved December 6, 2016 from http://forum.xda-developers.com/wiki/Root.

XDA Developers. 2015b. Android Recovery Wiki. Retrieved December 6, 2016 from http://forum.xda-developers.com/wiki/Recovery.

R. Xu, H. Saidi, and R. Anderson. 2012. Aurasium: Practical policy enforcement for Android applications. In *Proceedings of the 21st USENIX Conference on Security*.

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