# Java Cryptography Uses in the Wild

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## ABSTRACT

[Background] Previous research has shown that developers commonly misuse cryptography APIs. [Aim] We have conducted an exploratory study to find out how crypto APIs are used in open-source Java projects, what types of misuses exist, and why developers make such mistakes. [Method] We used a static analysis tool to analyze hundreds of open-source Java projects that rely on Java Cryptography Architecture, and manually inspected half of the analysis results to assess the tool results. We also contacted the maintainers of these projects by creating an issue on the GitHub repository of each project, and discussed the misuses with developers. [Results] We learned that 85% of Cryptography APIs are misused, however, not every misuse has severe consequences. Developer feedback showed that security caveats in the documentation of crypto APIs are rare, developers may overlook misuses that originate in thirdparty code, and the context where a Crypto API is used should be taken into account. [Conclusion] We conclude that using Crypto APIs is still problematic for developers but blindly blaming them for such misuses may lead to erroneous conclusions.

#### **KEYWORDS**

Java cryptography, security, empirical study

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# **1** INTRODUCTION

Cryptography is the primary mechanism for data protection in all privacy and security-sensitive services available in the digital world. Nevertheless, cryptography APIs (or "crypto APIs") are not easy to use for developers. A recent study reported that 72% of Java projects on GitHub suffer from at least one crypto misuse such as weak algorithm selection, short encryption key size, or obsolete function calls [5].

The lack of proper security-related hints in the common information sources for developers aggravates this issue. Oracle's official online documentation of the Java Cryptography Architecture (JCA) is mostly limited to the explanation of each API and its parameters, and it rarely explains caveats about secure configuration of the APIs. For example, the constructor of the PBEKeySpec class asks for an iterationCount parameter that specifies how many times the password is hashed to derive a crypto key [12]. Unfortunately the documentation does not indicate the minimum recommended value for this parameter.

Non-official documentation also suffers from similar issues. There are many cryptography questions on the Stack Overflow website, but the answers may be out of date, or the proposed solutions may not consider security implications. For instance, only fewer than 20% of examined posts suggest a secure solution to implement SSL certificate checks, and a considerable number of developers did not comprehend the security concept of coding options, *e.g.*, disabling the CSRF token [9].

Researchers actively attempt to improve the current state of using crypto APIs. For instance, a study of crypto uses in open-source projects claims that none of the factors such as the number or frequency of crypto-related code commits, or the number of projects that developers are involved in, correlate with developer performance in this domain [5]. An experiment with 53 developers shows that API-integrated security hints help 73% of developers to write more secure code [4]. In the same vein, researchers have provided developers with an interactive web platform to access correct uses of crypto APIs [6]. There also exist several static analysis tools such as CryptoLint [2], and CogniCrypt [7] to help developers spot crypto API misuses in programs.

In this work, we conduct an exploratory study to understand the current state of crypto API usage in open-source Java projects. In contrast to previous work, we investigate this topic at the API level i.e., we explain which APIs are problematic and what types of misuses prevail. We also contacted developers of these APIs to uncover the reasons underlying these misuses. In particular, we used the CogniCrypt static analysis tool to analyze hundreds of Java projects that rely on JCA APIs, and manually checked almost half of the results to understand the extent to which the tool result is reliable. We observed that crypto misuses are common; particularly, the majority of APIs (i.e., 13 of 15) were misused at least once. For instance, MessageDigest, the most prevalent JCA API in the projects, was misused in 92% of the cases. Our manual investigation revealed that the tool result is highly (i.e., 93%) reliable, however, in effect, the implications of a misuse depend on factors such as where and how the application is intended to be used. For instance, a crypto misuse that makes software vulnerable when running on a network may be used only locally. We prepared a publicly available dataset, called CryptoMine, containing the details of the analysis, e.g., project name, file name, API name, and line number.<sup>1</sup> We created issues on the GitHub repository of 216 projects to inform developers about crypto misuses. We collected feedback concerning 140 issue reports, and two authors of this paper reviewed and classified them into nine major categories, e.g., uncertain developers, non-security context, or lack of developer knowledge. Analyzing the developer responses revealed that in many cases developers are well-informed about the right usage of crypto APIs, but the

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<sup>&</sup>lt;sup>1</sup>http://crypto-explorer.com/cryptomine

specific code context may force them to misuse certain crypto APIs. However, other developers may be uncertain about correct API usage since security caveats in the crypto API documentation are scarce, or they used a third-party code that contained a misuse.

In the remainder of this paper, we describe the methodology of our work in section 2. Then, we describe the current status of the dataset and responses of developers in section 3. We point out potential threats to the validity of this work in section 4, and discuss related work in section 5. We conclude the paper in section 6.

# 2 METHODOLOGY

We followed a few main steps to analyze Java projects, build the CryptoMine dataset, and collect developer feedback on the crypto misuses. We explain these steps in the following.

#### 2.1 Searching, downloading, and compiling

We start with a set of projects that use JCA APIs and were identified in previous work [8]. We use GitHub APIs to fetch the collaborators of these projects and check what other Java projects they contributed to, which helps us to collect more projects. Next, we use the GitHub search code API to check whether a Java project uses any of the JCA APIs, such as MessageDigest, Cipher, or KeyStore. The GitHub search code API limits the number of requests to 30 per minute, therefore we execute this phase in parallel with different GitHub accounts. If the project is forked, then we clone the original repository. Forked projects significantly increase the chance of having duplicate projects in the dataset. We also did not limit our search criteria based on the number of project forks or stars, as we were only interested in collecting crypto API uses regardless of factors such as project size, popularity, or the degree of recent activity.

We compile each project in preparation for the static analysis phase. We use a bash script to check for the existence of the build file (POM) in the project's path and then proceed to compile the project using Maven. We exclude any projects that cannot be compiled due to unresolved dependencies.

#### 2.2 Analysis

We use an open-source static analysis tool called CogniCrypt, which detects known misuses of JCA APIs [7]. It uses a set of rules to analyze method-call patterns, parameter constraints, and secure compositions of cryptography-related classes. We chose CogniCrypt as it supports a wide range of APIs, is open-source, and relies on an extensive rule set created by crypto experts. We extended the tool to collect and report information regarding at what line number each API is used and in which user-defined method the API use occurred.

We feed each project's binary code (*i.e., .class* files) to CogniCrypt. Most projects are analyzed within 10 minutes. Accordingly, we abort lengthy analyses that take more than 15 minutes. Ultimately, 48 analyses were terminated.

For every successful analysis, we use the GitHub API to obtain general information regarding each project, *i.e.*, the number of stars, the number of forks, the creation and the last updated date of the project. 2.2.1 Schema. We use a bash script to extract information from the generated analysis reports with the help of regular expressions. We present the extracted values in the CryptoMine dataset as a comma-separated CSV file. Each record describes a single crypto API use. Table 1 presents each field and its description in a record. Each data record represents meta-information about a crypto API use in a project such as line number of the API use, Java file path containing the API use, or project's address on GitHub.

#### Table 1: Fields of each API use in CryptoMine

Field	Description				
ps_url	project's address on GitHub				
Star_count	number of stars of a project				
Fork_count	number of forks of a project				
Creation_date	creation date of a project				
Updated_date	last updated date of a project				
Last_visited	the last time we checked a project				
File_path	file path containing a crypto use				
S_object	status of a use (0 means a misuse, otherwise it is 1)				
API_name	name of the crypto API				
Line_number	line number of the crypto use				
User_method	the user-defined method where the crypto				
	API use is				
Misuse_type	A string referring to the type of the				
	crypto misuse (wrong type, wrong object,				
	wrong constraint, incomplete operation,				
	incomplete order)				
Misuse_desc	the description of the crypto misuse				
Manual_check	the manually checked status of an API use				
	(Accepted, Rejected, Unvalidated)				

The user\_method field provides information about the user-defined function where a crypto API use exists.

The misuse\_type field can represent any of the following five types provided by the static analysis tool. The "wrong type" means when a developer incorrectly uses a certain reference type. For instance, the constructor of PBEKeySpec requires the password to be passed as a character array, and should not be as a string object. The "wrong object" occurs when an object is passed to another object but not in the correct way to fulfill expected security requirements. The "wrong constraint", which is a common misuse type, occurs when a developer selects wrong values for integer or string objects to pass to a crypto API, like key sizes, algorithm names, or iteration counts. The "incomplete operation" indicates the whole path for the desired cryptographic purpose is not fulfilled, *e.g.*, failing to call PBEKeySpec.clearPassword(). Finally, the "incomplete order" shows that the expected method call sequence to be made is incorrect, *e.g.*, failing to call to init() in the Cipher API.

The misuse\_desc field explains for what reason, which is provided by the tool, a crypto API use violates CogniCrypt's rules. The "manual\_check" field indicates the manual cross-validation status of an API use. In case of approval, *i.e.*, agreement with the tool, we set the value of the field to *Accepted*, otherwise, the value is set to *Rejected*. Non-validated records are indicated by *Unvalidated*. Lastly, interested researchers can request to receive the cloned version of the projects. Java Cryptography Uses in the Wild

2.2.2 Manual investigation. Two authors of this paper manually checked 1280 records of CryptoMine (48% of the dataset). They relied on their expertise and the CrySL rules provided by the static analysis tool. The CrySL rules determine the secure uses of a crypto API. The reviewers examine the 1280 records separately and finally cross-check their individual judgments. In case of conflicts, they refer to the tool's rules and discuss them.

#### 2.3 Contacting the developers

To understand the reasons behind the misuses, we contacted 216 maintainers of repositories on GitHub, which represents a sample size with a 95% confidence level and 5% margin of error. For each repository, we opened an issue on the GitHub page, explained our objectives for reporting crypto misuses, provided an explanation for each misuse, and pinpointed the affected Java files, associated line numbers and API names. We waited 20 days for responses from the developers of repositories, and then we manually extracted their responses. Thereafter, two authors of this paper reviewed each response to determine the key message of each response. Finally, they cross-checked their findings and, in case of a conflict, they revisited the concerned response.

#### **3 RESULTS**

In this section we first report on the current status of crypto API uses in open-source projects, and then present the key messages of developer feedback.

## 3.1 The state of crypto uses

We investigated the use of 15 JCA APIs in 489 projects. We found that only two projects are completely healthy, and a staggering 487 projects suffer from at least one crypto misuse. The mean of the project forks is 139, and the median value is 7.5. The mean of the project stars is 348, and the median value is 5.

Among the manually investigated records, 74 records (6%) were flagged as rejected, which means according to the tool's rules and the opinions of reviewers they are mistakenly marked as misuses. For instance, before using the sign method in the Signature API, a developer needs to call either the initSign or the update method. However, in some cases, developers used the update method in a loop, while the automatic analysis could not recognize it.

Figure 1 summarizes the uses vs. misuses of each of these APIs as well as the total number of each API use in parenthesis. Developers seemingly have severe difficulties in using more than half of the APIs whose correct uses were less than 51%. For instance, The correct uses of five APIs namely, SecretKeySpec, IvParameter–Spec, KeyStore, Cipher, MessageDigest, and Signature were at most 10%. In contrast, developers had a promising performance in using the SecretKey, Mac, SecureRandom and KeyPair APIs, *i.e.*, at least 90% uses were correct.

Various misuse types may pose threat with different levels of severity depending on a project is intended to be used, *e.g.*, selecting a wrong constraint MD5 versus skipping to dispose of a crypto object. Table 2 gives information about the distribution of crypto misuse types in the top six most misused APIs. Most of the misuses were of the ConstraintError type followed by

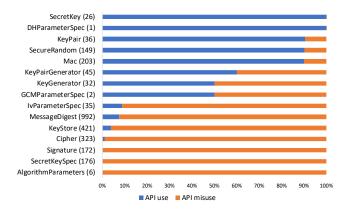


Figure 1: The misuses vs. uses of each API in percentage

type made up the largest proportion of misuses, showing that developers struggle with choosing correct parameters for crypto APIs. The second most common misuse is the RequiredPredicateError type, which means an insecure object is passed to other objects as an arguments. The NeverTypeOfError and IncompleteOperationError types account for nearly 23% of the total misuse types that exist in all analyzed projects.

The complete analysis results are publicly available via the CryptoMine dataset,<sup>2</sup> which facilitates investigation of the following research questions: (1) What are the most common crypto mistakes, and what should we do to improve learnability in this domain? (2) How do crypto uses evolve in a project? (3) How do the quality characteristics of a project correlate with crypto uses in that project? (4) In what context are crypto APIs commonly used? (5) Why do some developers perform better in using cryptography? (6) What is the performance of the static analysis tool in detecting crypto misuses? (7) What is the benchmark result of comparing several static analysis tools in detecting crypto uses of the dataset's projects?

# 3.2 Developer feedback

Out of 216 repository maintainers, 76 did not respond, and 140 reacted to the issues within 20 days. Among all the reported misused APIs, MessageDigest had the greatest number of submitted and received responses. KeyStore and SecretKeySpec are respectively in the second and third place with 22 and 15 received responses from 32 and 31 submitted issues. Following that, Cipher and Signature were the last two APIs that had been reported in more than 10 submissions. The rest of the APIs had only a few submission and received responses.

We evaluated all of the responses for 140 repositories in order to identify developer perceptions concerning cryptographic APIs. This widens our views on how knowledgeable developers are when they misuse a crypto API in their code.

We realized that only a tiny fraction of repository maintainers (*i.e.*, of seven repositories) agreed to fix the issues, and a large number of maintainers (*i.e.*, of 46 repositories) disagreed since the context where the misuse occurred was not considered to be

RequiredPredicateError and TypestateError. The ConstraintError<sup>2</sup>http://crypto-explorer.com/cryptomine

JCA API	IncompleteOperationError	NeverTypeOfError	TypestateError	RequiredPredicateError	ConstraintError
SecretKeySpec				170	
Signature	5		1	49	26
Cipher	42			83	52
KeyStore	32	160	16		
MessageDigest	72		178		400
IvParameterSpec				30	

#### Table 2: Mostly misused APIs with more than 10 misuse types

security-sensitive. Fortunately, 32 repository maintainers were interested in starting a dialogue about exactly why a given issue can cause problems, and whether the associated risks can arise in practice. We present nine main categories of responses in the following and highlight the key findings of each category in a box.

**Personal repository**. We received three responses indicating that the target repository is for a personal use. A contributor said that "the project is meant to be used for educational purposes and intentionally contains some vulnerable examples." Another mentioned that "the project is created for internal use and no issue will be addressed."

People are not aware of the impact these issues could have on those who rely on online examples, as their repositories are publicly accessible. Another facet could be that they are not concerned about security when a program is being used on a very small scale.

*Will fix later.* Developers of seven repositories replied that they will fix the reported crypto misuses later without asking for any further explanation. Three of them replied that those misuses do not affect the functionality of the program and are not urgent to be fixed.

Developers often underestimate the impact of a crypto misuse.

**Request for pull.** Developers of 17 repositories suggested to create a pull request. For instance, a contributor responded that *"T'm not sure if I understand the problem. I am not a cryptologist."* We believe a lack of knowledge in this area exists that may cause developers to blindly accept a pull request. The inevitable consequence of blindly accepting a pull request could adversely affect the security of the final software, for instance, an adversary may submit a downgrade to the existing security mechanisms in a project.

There is a risk that developers who lack security knowledge blindly accept security-related pull requests.

*Refer to the main library.* In five cases developers used an open-source library, and asked us to report the issue to the library's repository.

Unfortunately, developers seem not to be concerned about security risks associated with external libraries.

*Repo is not maintained.* We learned from the responses that 15 repositories are not maintained anymore.

Inactive projects are common in the open source community, for example due to a lack of financial support. However, as long as the code is available online, novice developers may rely on open-source projects irrespective of how active the projects are.

Consult documentation. Developers of 10 repositories were not completely certain about how the APIs should be used securely. They either asked us to read the API documentation or quoted a relevant part of the documentation in their responses. For instance, we suggested not to use java.lang.String as the second parameter of KeyStore, which is the password parameter. They replied that "according to the documentation, the parameter is a String, so why should it never be?" One responded that "MD5 is still supported by java according to the Java documentation." Another one asked us to provide him with the correct use of Signature API as he did not know how to fix it. A developer referred to the official Java documentation to express his trust in using the SHA1withRSA algorithm in the Signature API. Developers of two repositories were not convinced to stop using NoPadding in the Cipher API. They noted that using an *empty string* in Java 8 can cause a run-time error and they cited Cipher's page in Java documentation.

Developers have confidence in official documentation, but security concerns are mainly absent in such resources.

**Uncertainty**. We found that many developers (*i.e.*, of 32 repositories) asked us to provide a clarification. Some developers referred to blog posts where the KeyStore API was misused by converting a string variable to an array of characters, *i.e.*, *password.toCharArray()*, and passing it as the second parameter to the API. A common skepticism was about which algorithm is safe to use in SecretKeySpec and KeyPairGenerator.

A few developers asked how the misuses can be exploited in real life. For instance, a contributor was not convinced about the nature of the "misuse" as it was not clear to him how a wrong transformation mode in the Cipher API can be exploited in his application.

As expected, developer uncertainty regarding the correct way of using an API securely is related to either the right method call or the secure algorithm name

**Consider the context and disagreement**. The majority of responses (46) are connected with the context of the code. A large number of these responses were mainly related to the MessageDigest API since MessageDigest was used more frequently than any other crypto API in the analyzed projects. This is because MessageDigest

can be used in many different scenarios such as authentication, checksumming, archiving, or in combination with other algorithms.

One common complaint was that MD5 or SHA1 were not being used for security purposes. They had been used for archiving or producing hashes for non-security use-cases. For instance, one developer mentioned that the Redis API needs to generate checksums using SHA1. As another example of non-security usage, one repository used SHA1 for opening a handshake in WebSocket and the contributor referred to the RFC 6455 section 1.3 for further information. Moreover, three repository maintainers replied that instead of using String.hashCode(), they used SHA1/MD5 as an internal identifier, i.e., generating a normalized document ID based on the URL of the given document. Another developer stressed that they use MD5 in order to track if the template source has been changed or not. A group of developers used MD5 to get a hash of an email address to produce the avatar URL of the user. SHA1 was also used in a for loop to generate fake data to be stored in a file in a repository. Contributors to a repository pointed to a code comment preceding the SHA1 usage that clearly says that SHA1 was used only to generate a single hash for the entire contents of a folder and it is absolutely sufficient.

Some contributors complained that the critiqued code is very old and the context is not security-focused, *i.e.*, a decade old, and running a static analysis is not a good measure to find misuses. In some responses, they did not exactly mention what the context was and only replied that the context is not security-sensitive. For example, we manually checked the codes of the repositories and found that MessageDigest was used for purposes such as hashing parameters, *i.e.*, album name, in the URL or to cache the unpacked ZIP file and avoid multiple extractions.

In one repository, developers indicated that there was a code comment explaining why the Signature API had been used in an insecure way. A developer mentioned that although KeyPairGenerator accepts many algorithms such as RSA, DSA, and Diffie-Hellman, in this project the APNs protocol demands KeyPairGenerator to generate key pairs for the Elliptic Curve algorithm.

One contributor cited a blog post where the blogger discussed that SHA1 is still usable regardless of the existing collision vulnerability. He insisted that they will continue using the algorithm until a serious security problem is raised by using SHA1. Another developer stressed that MySQL authentication plugins do not support the usage of SHA-256 and accordingly, SHA1 was used in their project. In contrast, official MySQL documentation added that since MySQL 5.6, the sha256\_password authentication plugin is supported. With regard to the misuse of MD5, a developer replied that he cannot change the algorithm name as the remote endpoint requires an MD5 hash and he is not able to change it on the remote endpoint.

Developers mainly argued that their context is not related to security. The use of security APIs to produce hashes was the most common non-security related usage.

We witnessed that some APIs were more prevalent compared to others in our reports. For example, the MessageDigest API was seen more than other APIs in all response categories except for "Personal repository." In MessageDigest, the most common misuse type is *constraint error* in which developers used the MD5 or SHA1 algorithms to compute hashes. As hashing algorithms could be used for non-security purposes, many maintainers were expected to note that the context is not relevant. KeyStore and Cipher are the second most frequently seen APIs in the responses. Repository maintainers mostly asked for clarification or referred to the documentation of Java for the misuses of KeyStore. The Cipher API had the majority of misuses linked to its first argument. This occurred due to the diversity of options in the transformation string. A transformation string includes the name of a cryptographic algorithm (e.g., AES or DES), and may be followed by a feedback mode and padding scheme, *e.g.*, "algorithm/mode/padding". On the whole, developers had difficulty in understanding what constraint they should pass to the crypto APIs or how to create an object securely in order to pass it to another crypto API.

The responses of maintainers highlight the fact that some developers are fully aware of what they are doing, whereas others have doubts concerning the correct way of using such APIs. As a result, blaming only developers for the found crypto API misuses cannot be correct. To highlight the leading causes of crypto misuses, we identify various influential factors that must be taken into account. The age of a project can be an essential factor as security standards can evolve over time. Another factor is to blindly rely on the use of third-party libraries. Developers need to spend more time and select libraries with higher credibility and support. Official documentation and unofficial online documentation, such as Stack Overflow, can have pernicious effects on developer choice. This impact can be ruinous when the developer lacks the minimum knowledge in the domain of cryptography, e.g., choosing ECB mode from the examples provided by the official documentation. Furthermore, such developers may not be able to make a good use of static analysis tools to resolve their crypto problems. On the other hand, statically checking the developer's code without considering the context yields misleading results and could not be a dependable measure for developer performance in this domain. For instance, recent program analysis tools consider SHA-1 to be insecure. Such tools produce alerts if a developer cautiously uses three nested SHA-1 to produce a hash while the application is not, indeed, exposed to security threats. Lastly, even though some developers were aware of the right crypto usage, the widespread of such examples on opensource projects may have profound implications on inexperience developers.

## **4 THREATS TO VALIDITY**

It is infeasible to manually identify crypto (mis)uses in source code at large-scale. Adoption of static code analysis tools can considerably help developers to automatically detect crypto misuses and write more secure code. Therefore, we employed a static analysis tool, *i.e.*, CogniCrypt, in order to assess the status of crypto uses in hundreds of Java projects. The primary reason for this choice is that the tool is open-source and supports a wide range of crypto rules for different APIs, which are easily extendable. However, the CryptoMine dataset does not represent all the JCA APIs and their various usages, *e.g.*, different parameters or method calls. This can be addressed by increasing the number of analyzed projects which contain different usages of crypto APIs. To provide a better level of reliability, we have manually cross-checked 48% of the results in the CryptoMine dataset. Nevertheless, the manual analysis of a large dataset is a non-trivial task and to accelerate the process we invite interested researchers to join us. Moreover, security assumptions may change over a period of time. For instance SHA1, which was judged to be secure in the past, is considered insecure now. Further work is needed to add an extensive range of API usages and to contact more repositories to collect more evidence for the corresponding API misuses.

#### **5 RELATED WORK**

A series of recent studies have indicated that developers need more security support from different aspects, e.g., secure documentation, secure sample code, to write secure code. Nadi et al. surveyed two groups of developers, i.e., 11 developers who had crypto-related questions on Stack Overflow, and 37 developers who used Java's cryptography APIs. The authors realized that developers are certain in choosing the proper cryptography concepts, but problems still exist in using certain cryptographic algorithms correctly. They arrived at the conclusion that crypto APIs are generally regarded to be too low-level, and developers choose more task-based solutions [10]. In a study, Acar et al. asked 54 participants to solve pre-defined challenges in which the participants had to write security- and privacy-relevant code under time limitations [1]. The authors noticed that many of the security problems made by their participants also can be found on online sources, e.g., Stack Overflow. Conducting a controlled experiment with 53 participants, Gorski et al. showed the effectiveness of API-integrated security advice can significantly help (i.e., 73%) to produce more secure code [4].

Previous studies have emphasized that developers commonly misused crypto APIs. Rahman et al. used their static analysis tool, named CHIRON, to evaluate 46 large-scale Apache projects [11]. They found a total of 2,009 alerts in the projects. Egele et al. developed a static analysis tool, i.e., CryptoLint, and tested on 11,748 applications using cryptographic APIs [2]. Their results indicated that 88% of the applications used crypto APIs inappropriately. Krüger et al. introduced a tool called CogniCrypt, an Eclipse plugin that assists developers to securely use cryptographic API [8]. CogniCrypt also presents secure code templates so as to reduce the hassle of searching for secure API usages. Besides, CogniCrypt employs CrySL that empowers cryptographic specialists to expand the rules for other APIs[7]. Gao et al. made an assumption that developers update API usage instances to fix misuses, and accordingly, conducted a large scale analysis on nearly 40 000 real-world app lineages to trace API usage rules [3]. They failed to confirm their assumption that API usage updates tend to fix misuses.

# 6 CONCLUSION

We analyzed hundreds of projects in which JCA APIs were used, to observe the status of API use in open-source projects, to learn what crypto misuse types exist, and to investigate the influential factors in misusing such APIs. We found that 85% of the crypto APIs suffered from at least one misuse, though not all misuses were at the same level of severity. We contacted the maintainers of the projects to understand the reasons behind the misuse of crypto APIs, and we classified their responses into nine main categories. The results demonstrate that security hints in API documentation are scarce, misuses are rooted in third-party libraries, or the code context plays a crucial role in using crypto APIs incorrectly. Finally, to support the research community, we publicly share the CryptoMine dataset, including the analysis results, and information about each project such as its metadata information, the precise locations of API use, and the safety status of these APIs, to name but a few.

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