CrySL: Validating Correct Usage of Cryptographic APIs

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ABSTRACT

Various studies have empirically shown that the majority of Java and Android apps misuse cryptographic libraries, causing devastating breaches of data security. Therefore, it is crucial to detect such misuse early in the development process. The fact that insecure usages are not the exception but the norm precludes approaches based on property inference and anomaly detection.

In this paper, we present CrySL, a definition language that enables cryptography experts to specify the secure usage of the cryptographic libraries that they provide. CrySL combines the generic concepts of method-call sequences and data-flow constraints with domain-specific constraints related to cryptographic algorithms and their parameters. We have implemented a compiler that translates a CrySL ruleset into a context- and flow-sensitive demand-driven static analysis. The analysis automatically checks a given Java or Android app for violations of the CrySL-encoded rules.

We empirically evaluated our ruleset through analyzing 10,001 Android apps. Our results show that misuse of cryptographic APIs is still widespread, with 96% of apps containing at least one misuse. However, we observed fewer of the misuses that were reported in previous work.

KEYWORDS

cryptography, domain-specific language, static analysis

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1 INTRODUCTION

Digital devices are increasingly storing sensitive data, which is often protected using cryptography. However, it is insufficient to use secure cryptographic algorithms. A developer must also know how to securely use such algorithms in their code. Unfortunately, prior studies suggest that this is rarely the case. Lazar et al. [17] examined 269 published cryptography-related vulnerabilities. They found that 223 are caused by developers misusing a security library, and only 46 result from faulty library implementations. Egele et al. [12] statically analyzed 11,748 Android apps using cryptography-related application interfaces (Crypto APIs) and found 88% of them violated at least one basic cryptography rule. Chatzikokonstantinou et al. [11] reached a similar conclusion by first analyzing apps dynamically and then performing a manual inspection for misuses.

Such pervasive insecure use of cryptographic libraries is problematic for several reasons. First, the misuses of Crypto APIs lead to devastating data breaches in a large number of applications. Rasthofer et al. [25] show that virtually all smartphone apps that rely on cloud services use hard-coded keys. A simple decompilation gives adversaries access to those keys, and to all data that all these apps store in the cloud. Nadi et al. [22] were the first to investigate why developers often struggle to use Crypto APIs. The authors conducted four studies, two of which survey Java developers familiar with the Java Crypto APIs. The majority of participants (65%) found their respective Crypto APIs hard to use. When asked why, participants mentioned the API level of abstraction, insufficient documentation without examples, and API design make it difficult to understand how to properly use Crypto APIs. A potential long-term solution is redesigning the APIs to provide an easy-to-use interface for developers that is secure by default. However, it remains crucial to detect and fix the existing insecure API uses. When asked about what would simplify their API usage, participants wished they had tools that help them automatically detect misuses and suggest possible fixes Nadi et al. [22]. Unfortunately, approaches based solely on specification inference and anomaly detection [26] are not viable for Crypto APIs, because—as elaborated above—most uses of Crypto APIs are insecure.

In this paper, we present (a) CrySL, a definition language that enables cryptography experts to specify the secure usage of their Crypto APIs, and (b) CogniCryptSAST, a compiler that parses and type-checks CrySL rules and translates them into a static analysis. The analysis automatically checks a given Java or Android app for compliance with the encoded CrySL rules. CrySL goes beyond methods that are useful for general validation of API usage (e.g., typestate analysis [2, 7, 8, 23] and data-flow checks [1, 5]) by enabling the expression of domain-specific constraints related to cryptographic algorithms and their parameters. Our focus is the Java Cryptography Architecture (JCA), because it is the primary cryptography API for Java applications [22]. To evaluate CrySL, we encoded a comprehensive ruleset for the JCA classes and interfaces, and we used the generated static analysis to scan 10,001
SecretKeyGenerator kG =
    KeyGenerator.getInstance("AES");
kG.init(128);
SecretKey cipherKey = kG.generateKey();
Cipher cipher = Cipher.getInstance(Cipher.ENCRYPT_MODE, cipherKey);
byte[] cipherText =
    cipher.doFinal(plaintextMSG.getBytes("UTF-8"));

Figure 1: An example illustrating the use of java.security.KeyGenerator to implement data encryption in Java.

Figure 2: Basic CrySL syntax elements.

Android apps that use the JCA, CogniCryptSAST found at least one misuse in 96% of the apps. For more than 75% of the apps, CogniCryptSAST finishes in under 4 minutes.

In summary, this paper presents the following contributions:

- We introduce CrySL, a definition language to specify correct usages of Crypto APIs.
- We encode a comprehensive specification of correct usages of the JCA in CrySL.
- We present CogniCryptSAST, a compiler that translates CrySL rules into a static analysis to find violations in a given Java or Android app.
- We empirically evaluate CogniCryptSAST on 10,001 Android apps.

We will open source our implementation and artifacts on GitHub.

Figure 3: A CrySL rule in Extended Backus-Naur Form (EBNF) [6].

2 MOTIVATING EXAMPLE

Throughout the paper, we will use the code example in Figure 1 to motivate the language features in CrySL.

MOTIVATING EXAMPLE

Throughout the paper, we will use the code example in Figure 1 to motivate the language features in CrySL. Lines 1–3 generate a 128-bit secret key to use with the encryption algorithm AES. Lines 5–7 use that key to initialize a Java Cipher object that encrypts plaintextMSG. Since AES encrypts plaintext block by block, it must be configured to use one of several modes of operation. The mode of operation determines how to encrypt a block based on the encryption of the preceding block(s). Line 6 configures Cipher to use the Galois/Counter Mode (GCM) of operation [20].

Although the code example may look straightforward, there are a number of subtle mistakes that render the encryption insecure. First, both KeyGenerator and Cipher only support a limited choice of encryption algorithms. If the developer passes an unsupported algorithm to either getInstance methods, the respective line will throw a runtime exception. Similarly, the design...
of the APIs separates the classes for key generation and encryption. Therefore, the developer needs to make sure they pass the same algorithm to the getInstance methods of KeyGenerator and Cipher. If the developer does not configure the algorithms as such, the generated key will not fit the encryption algorithm, and the encryption will fail by throwing a runtime exception. Moreover, some supported algorithms are no longer considered secure (e.g., DES or AES/ECB [14]). If the developer selects such an algorithm, the program will still run to completion, but the resulting encryption will be insecure.

To use Crypto APIs properly, developers have to take two dimensions of correctness into consideration: (1) the functional correctness that allows the program to run and terminate successfully and (2) the provided security guarantees. Prior empirical studies have shown that developers frequently succeed in obtaining functional correctness by, for instance, looking for code examples on web portals such as StackOverflow [13]. However, they often fail to obtain a secure use of Crypto APIs, primarily because most code examples on those web portals provide insecure solutions [13].

3 CRYSL SYNTAX

Instead of relying on the security of existing usages and examples, we present an approach in which cryptography experts define correct API usages in a domain-specific language, CrySL. In this section, we give an overview of the CrySL syntax elements. A formal treatment of the CrySL semantics is presented in Section 4. Figure 2 presents the basic syntactic elements of CrySL, and Figure 3 presents the full syntax for a CrySL rule. Figure 4 shows an abbreviated CrySL rule that defines the correct usage of javax.crypto.KeyGenerator in the example in Figure 1.

3.1 Mandatory Sections in a CrySL Rule

To provide simple and reusable constructs, a CrySL rule is defined on the level of individual classes. Therefore, the rule starts off by stating the class that it is defined for.

In Figure 4, the OBJECTS section defines four objects to be used in later sections of the rule (e.g., the object algorithm of type String). These objects are typically used as parameters or return values in the EVENTS section.

The EVENTS section defines all methods that may contribute to the successful usage of a KeyGenerator object, including three getInstance methods that are defined by two method event patterns (Lines 17–18). The first parameter of all three methods is a String object whose value states the algorithm that the key should be generated for. This parameter is represented by the previously defined algorithm object. Two of the getInstance methods are overloaded with two parameters. Since we do not need to specify the second parameter in either method, we substitute it with an underscore that serves as a placeholder in one combined pattern definition (Line 18). Finally, the rule defines patterns for the various init methods that set the proper parameter values (e.g., keysize) and a generateKey method that completes the key generation and returns the generated key.

Line 30 defines a usage pattern for KeyGenerator using the keyword ORDER. The usage pattern is a regular expression of method event patterns that are defined in EVENTS. Although each method pattern defines a label to simplify referencing related events (e.g., g1, 12, and GenKey), it is tedious and error-prone to require listing all those labels again in the ORDER section. Therefore, CrySL allows defining aggregates. An aggregate represents a disjunction of multiple patterns by means of their labels. Line 19 defines an aggregate that groups the two getInstance patterns. Using aggregates, the usage pattern for KeyGenerator reads: there must be exactly one call to one of the getInstance methods, followed by an optional call to one of the init methods, and finally a call to generateKey.

Following the keyword CONSTRAINTS, Lines 33–35 define the constraints for objects defined under OBJECTS and used as parameters or return values in the EVENTS section. In the abbreviated CrySL rule in Figure 4, the first constraint limits the value of algorithm to AES or Blowfish. For each algorithm, there is one constraint that restricts the possible values of keysize.

The ENSURES section is the final mandatory construct in a CrySL rule. The section specifies predicates to govern interactions between different classes. For example, a Cipher object uses a key obtained from a KeyGenerator. The ENSURES section specifies what a class provides, presuming that the object is used properly. For example, the KeyGenerator CrySL rule in Figure 4 ends with the definition of a predicate generateKey with the generated key object and its corresponding algorithm as parameters. This predicate may be required by the rule for Cipher or other classes that make use of such a key through the optional element of the REQUIRE block as illustrated in Figure 5.
3.2 Optional Sections in a CrySL Rule

A CrySL rule may contain optional sections that which we will showcase through the CrySL rule for PBEKeySpec. In Figure 6, the FORBIDDEN section specifies methods that should not be called, because calling them is always insecure. PBEKeySpec derives cryptographic keys from a user-given password. For security reasons, it is recommended to use a cryptographic salt for this operation. However, the constructor PBEKeySpec(char[] password) does not allow for a salt to be passed and the implementation in the default provider does not generate one. Therefore, this constructor should not be called, and any call to it should be flagged. Consequently, the CrySL rule for PBEKeySpec lists it in the FORBIDDEN section (Line 72). In the case of PBEKeySpec, there is an alternative secure constructor (Line 68). CrySL allows specifying an alternative method pattern event using the arrow notation (Line 72).

In general, predicates are generated for a particular usage only if it follows the usage pattern defined in the ORDER section and fulfills all constraints in the CONSTRAINTS section of its corresponding rule. However, PBEKeySpec differs from that pattern. The class contains a constructor that receives a user-given password, but the method clearPassword deletes that password later. Consequently, a PBEKeySpec object fulfills its role after calling the constructor until clearPassword is called. To support this usage, CrySL allows specifying a method event pattern that if called, a predicate is generated using the keyword after (Line 80). CrySL further supports killing an existing predicate in the NEGATES section (Line 83).

4 CRYSL FORMAL SEMANTICS

4.1 Basic Definitions

A CrySL rule consists of several sections. The OBJECTS section comprises a set of typed variable declarations \( \mathcal{V} \). In the syntax in Figure 3, each declaration \( v \in \mathcal{V} \) is represented by the syntax \( \text{TYPE} \ varname \). The EVENTS section contains elements of the form \((m,v)\), where \( m \in \mathcal{M} \) and \( v \in \mathcal{V}^* \). \( \mathcal{M} \) is the set of all resolved method signatures, where each signature includes the method name and argument types. The FORBIDDEN section lists a set of methods \( \mathcal{M} \) denoted by their signatures; forbidden events cannot bind any variables. The ORDER section specifies the usage pattern in terms of a regular expression of labels or aggregates that are in \( \mathcal{M} \). We express this regular expression formally by the equivalent non-deterministic finite automaton \((Q,M,\delta,q_0,F)\) over the alphabet \( \mathcal{M} \), where \( Q \) is a set of states, \( q_0 \) is its initial state, \( F \) is the set of accepting states, and \( \delta : Q \times \mathcal{M} \rightarrow \mathcal{P}(Q) \) is the state transition function.

The CONSTRAINTS section is a subset of \( \mathcal{C} := (\mathcal{V} \rightarrow \mathcal{O} \cup \mathcal{V}) \rightarrow \mathcal{B} \), i.e., each constraint is a boolean function, where the argument is itself a function that maps variable names in \( \mathcal{V} \) to objects in \( \mathcal{O} \) with values of primitive types in \( \mathcal{V} \).

A CrySL rule is a tuple \((T,E,A,C)\), where \( T \) is the reference type specified by the SPEC keyword, \( E \subseteq \mathcal{M} \) is the set of forbidden events, \( A = (Q,M,\delta,q_0,F) \in \mathcal{A} \) is the automaton induced by the regular expression of the ORDER section, and \( C \subseteq \mathcal{C} \) is the set of CONSTRAINTS that the rule lists.

Our formal definition of a CrySL rule does not contain the sections REQUIRES, ENSURES, and NEGATES. Those sections reason about the interaction of predicates, which requires a different formal treatment that we discuss in Section 4.2.2.
4.2 Runtime Semantics

Each CrySL rule encodes usage constraints to be validated for all runtime objects of the reference type $T$ stated in its SPEC section. We define the semantics of a CrySL rule in terms of an evaluation over a runtime program trace that records all relevant runtime objects and values, as well as all events specified within the rule.

**Definition 1 (Event).** An event is a tuple $(m, e) \in \mathbb{E}$ of a method signature $m \in \mathbb{M}$ and an environment $e$, i.e., a mapping $\forall \rightarrow O \cup V$ of the parameter variable names to concrete runtime objects and values. If the environment $e$ holds a concrete object for the this value, then it is called the event’s base object.

**Definition 2 (Runtime Trace).** A runtime trace $\tau \in \mathbb{E}^*$ is a finite sequence of events $\tau_0, \ldots, \tau_n$.

**Definition 3 (Object Trace).** For any $\tau \in \mathbb{E}^+$, a subsequence $\tau_{i_1}, \ldots, \tau_{i_n}$ is called an object trace if $i_1 < \ldots < i_n$ and all base objects of $\tau_{i_j}$ are identical.

Lines 1–2 in Figure 1 result in an object trace that has two events:

$$\left( m_0, \{ \text{algorithm} \rightarrow “AES”, \text{this} \rightarrow o_{kg} \} \right)$$

$$\left( m_1, \{ \text{algorithm} \rightarrow “AES”, \text{keySize} \rightarrow 128, \text{this} \rightarrow o_{kg} \} \right)$$

where $m_0$ and $m_1$ are the signatures of the getInstance and init methods of the KeyGenerator class. For static factory methods such as getInstance, we assume this to bind to the returned object. $o_{kg}$ denotes the object that at runtime is bound to the variable $kg$.

The decision whether a runtime trace $\tau$ satisfies a set of CrySL rules involves two steps. In the first step, individual object traces are evaluated independently of one another. Yet, different runtime objects may still interact with each other. CrySL rules capture this interaction by means of predicates that a rule ensures on a runtime object. These interactions between different objects are checked in a second step against the specification by considering the predicates they require and ensure. We now discuss these steps in more detail.

4.2.1 Individual Object Traces. The sections FORBIDDEN, ORDER and CONSTRAINTS are evaluated on individual object traces. Figure 7 defines the function $sat^o$ that is true if and only if a given trace $\tau^o$ for an object $o$ satisfies its CrySL rule. This definition of $sat^o$ ignores interactions with other object traces. We will discuss later how such interactions are resolved. In the following, we assume the trace $\tau^o = \tau^o_0, \ldots, \tau^o_n$, where $\tau^o_i = (m^o_i, e^o_i)$. We will also refer to our example from Figure 1 and the involved rules of KeyGenerator (Figure 4) and Cipher (Figure 5) to illustrate the computation. The function $sat^o$ is composed of three sub-functions:

**Forbidden Events ($sat^o_F$).** Given a trace $\tau^o$ and a set of forbidden events $E$, $sat^o_F$ ensures that none of the trace events is forbidden.

$$sat^o_F(\tau^o, E^o) := \bigwedge_{i=0, \ldots, n} m^o_i \notin E^o$$

The CrySL rule for KeyGenerator does not list any forbidden methods. Hence, $sat^o_F$ trivially evaluates to true for object $kg$ in Figure 1.
4.2.2 Interaction of Object Traces. To define interactions between individual object traces, the \textbf{REQUIRES}, \textbf{ENSURES}, and \textbf{NEGATES} sections allow individual CrySL rules to reference one another. For a rule for one object to hold at any given point in an execution trace, all predicates that its \textbf{REQUIRES} section lists must have been both previously \textit{ensured} (by other specifications) and not \textit{negated}. Predicates are \textit{ensured} (i.e., generated) and \textit{negated} (i.e., killed) by certain events. Formally, a predicate is an element of $\mathcal{P} := \{(\text{name}, \text{args}) | \text{args} \in \mathbb{V}^*\}$, i.e., a pair of a predicate name and a sequence of variable names. Predicates are generated in specific states. Each CrySL rule induces a function $G: S \rightarrow \mathcal{P}(\mathcal{F})$ that maps each state of its automaton to the predicate(s) that generate the state.

The predicates listed in the \textbf{ENSURES} and \textbf{NEGATES} sections may be followed by the term \texttt{after} $n$, where $n$ is a method event pattern label or an aggregate. The states that follow the event or aggregate $n$ in the automaton generate the respective predicate. If the term \texttt{after} is not used for a predicate, the final states of the automaton generate (or negate) that predicate, i.e., we implicitly interpret it as \texttt{after} $n$, where $n$ is an event that leads to a final state.

In addition to states that are selected as predicate-generating, the predicate is also ensured if the object resides in any state that transitively follows the selected state, unless the states are explicitly (de-)selected for the same predicate within the \textbf{NEGATES} section.

At any state that generates a predicate, the event driving the automaton into this state binds the variable names to the values that the specification previously collected along its object trace.

Formally, an event $n^o = (m^o, e^o) \in \mathcal{E}$ of a rule $r$ and for an object $o$ ensures a predicate $p = (\text{predName}, \text{args}) \in \mathcal{P}$ on the objects $e^o \in O$ if:

1. The method $m^o$ of the event leads to a state $s$ of the automaton that generates the predicate $p$, i.e. $p \in G(s)$.
2. The runtime trace of the event’s base object $o$ satisfies the function $sat^o$.
3. All relevant \textbf{REQUIRES} predicates of the rule are satisfied at execution of event $n^o$.

For the KeyGenerator object $kG$ in Figure 1, a predicate is generated at Line 7 because (1) its automaton transitions to its only predicate-generating state, state 2, (2) $sat^o$ evaluates to true as previously shown for each subfunction and (3) the corresponding CrySL rule does not require any predicates.

5 DETECTING MISUSES OF CRYPTO API

To detect all possible rule violations, our tool CogniCryptSAST approximates the evaluation function $sat^o$ using a static data-flow analysis. In a security context, it is a requirement to detect as many misuses as possible. A drawback of this potential is the potential for false warnings that originate from over-approximations that the static analysis requires. In the following, we use the example in Figure 9 to illustrate why and where approximations are required. We will show later in our evaluation that, in practice, our analysis is highly precise and that the chosen approximations rarely lead to false warnings.

The code example in Figure 9 implements a hashing operation. By default, the code uses SHA-256 for the operation. However, if the condition option1 evaluates to true, MD5 is chosen instead (Line 88). The CrySL rule for MessageDigest, displayed in Figure 10, does not allow the usage of MD5 though, because MD5 is no longer secure [14].

The update operation is performed only on non-empty input (Line 91). Otherwise, the call to update is skipped and only the call to digest is executed, without any input. Although not strictly insecure, this usage does not comply with the CrySL rule for MessageDigest, because it leads to no content being hashed.

To approximate $sat^o$, the analysis must search for possible forbidden events by first constructing a call graph for the whole program under analysis. It then iterates through the graph edges to
find calls to forbidden methods. Depending on the precision of the call graph, the analysis may find calls to forbidden methods that cannot be reached at runtime.

The analysis represents each runtime object \( o \) by its allocation site. In our example, allocation sites are new expressions and getInstances calls that return an object of a type for which a CrySL rule exists. For each such allocation site, the analysis approximates \( \text{sat}^o \) by first creating a state-machine. CognitoCrypt\text{\textsubscript{AST}} then evaluates the state machine using a typestate analysis that abstracts runtime traces by program paths. The typestate analysis is path-insensitive, thus, at branch points, it assumes that both sides of the branch may execute. In our example, this feature leads to a false positive: although the condition in Line 91 always evaluates to true, and the call to update is never actually skipped, the analysis considers that this may happen, and thus reports a rule violation.

To approximate \( \text{sat}^o \), we have extended the typestate analysis to also collect potential runtime values of variables along all program paths where an allocated object is used. The constraint solver first filters out all irrelevant constraints. A constraint is irrelevant if it refers to one or more variables that the typestate analysis has not encountered. In Figure 10, the rule only includes one internal constraint—on variable algorithm. If we add a new internal constraint to the rule about the variable offset, the constraint solver will filter it out as irrelevant when analyzing the code in Figure 9, because the only method that this variable is associated with (digest labeled d3) is never called. The analysis distinguishes between never encountering a variable in the source code and not being able to extract the values of a variable. Using the same rule and code snippet, if the analysis fails to extract the value for algorithm, the constraint evaluates to false. Collecting potential values of a variable over all possible program paths of an allocation site may lead to further imprecision. In our example, the analysis cannot statically rule out that algorithm may be MD5. The rule forbids the usage of MD5. Therefore, the analysis reports a misuse.

Handling predicates in our analysis follows the formal description very closely. If \( \text{sat}^o \) evaluates to true for a given allocation site, the analysis checks whether all required predicates for the allocation site have been ensured earlier in the program. In the trivial case, when no predicate is required, the analysis immediately ensures the predicate defined in the \text{ENSURES} section. The analysis constantly maintains a list of all ensured predicates, including the statements in the program that a given predicate can be ensured for. If the allocation site under analysis requires predicates from other allocation sites, the analysis consults the list of ensured predicates and checks whether the required predicate, with matching names and arguments, exists at the given statement. If the analysis finds all required predicates, it ensures the predicate(s) specified in the \text{ENSURES} section of the rule.

6 IMPLEMENTATION

We have implemented CognitoCrypt\text{\textsubscript{AST}} using Xtext [16], an open-source framework for developing domain-specific languages. Given the CrySL grammar, Xtext provides a parser, type checker, and syntax highlighter for the language. When supplied with a type-safe CrySL rule, Xtext outputs the corresponding AST, which CognitoCrypt\text{\textsubscript{AST}} then uses to generate the required static analysis. For the static analysis, we use the program analysis framework Soot [30]. Soot transforms a given Java program into an intermediate representation that facilitates executing intra- and inter-procedural static analyses. The framework provides standard static analyses such as call graph construction. Additionally, Soot can analyze a given Android app intra-procedurally. Further extensions by FlowDroid [5] enable the construction of Android-specific call graphs that are necessary to perform inter-procedural analysis.

Validating the \text{ORDER} section requires solving the typestate check \( \text{sat}^o \). To achieve this, we use IDE\text{\textsubscript{al}}, a framework for efficient inter-procedural data-flow analysis [28], to instantiate a typestate analysis. The analysis defines the finite state machine \( \mathcal{A}^o \) to check against and the allocation sites to start the analysis from. From those allocation sites, IDE\text{\textsubscript{al}} performs a flow-, field-, and context-sensitive data-flow analysis.

The constraints and the predicates require knowledge about objects and values associated with rule variables at given execution points in the program. The typestate analysis in CognitoCrypt\text{\textsubscript{AST}} extracts the primitive values and objects on-the-fly, whereas the latter are abstracted by allocation sites. When the typestate analysis encounters a call site that is referred to in an event definition, and the respective rule requires the object or value of an argument to the call, CognitoCrypt\text{\textsubscript{AST}} triggers an on-the-fly backward analysis to extract the objects or values that may participate in the call. This on-the-fly analysis yields comparatively high performance and scalability, because many of the arguments of interest are values of type String and Integer. Thus, using an on-demand computation avoids constant propagation of all strings and integers through the program. For the on-the-fly backward analysis, we extended the on-demand pointer analysis Boomerang [29] to propagate both allocation sites and primitive values.

Once the typestate analysis is completed, and all required queries to Boomerang are computed, CognitoCrypt\text{\textsubscript{AST}} solves the internal constraints and predicates using our own custom-made solvers.

7 EVALUATION

We evaluate our implementation of CrySL and CognitoCrypt\text{\textsubscript{AST}} by addressing the following research questions:

**RQ1:** What are the precision and recall of CognitoCrypt\text{\textsubscript{AST}}?

**RQ2:** What types of misuses does CognitoCrypt\text{\textsubscript{AST}} find?

**RQ3:** How fast does CognitoCrypt\text{\textsubscript{AST}} return results?

**RQ4:** How does CognitoCrypt\text{\textsubscript{AST}} compare to the state-of-the-art?

To answer these questions, we developed CrySL rules for all JCA classes. We then applied CognitoCrypt\text{\textsubscript{AST}} using this ruleset to statically analyze 10,001 Android apps from the AndroZoo dataset [3]. We chose apps that are available in the official Google Play Store and received an update in 2017. This ensures that we report on the most up-to-date usages of Crypto APIs. Our project web page lists all apps in our dataset and our CrySL ruleset to facilitate reproduction: http://cryptoapis.wordpress.com

During our evaluation, CognitoCrypt\text{\textsubscript{AST}} frequently reported misuses within packages for commonly used libraries across different apps. To avoid over-counting the same misuses, we excluded the following common library packages: com.google, com.unity3d, com.facebook.ads, and com.android.
7.1 Precision and Recall (RQ1)

Setup. To compute precision and recall, two authors of this work manually checked 50 randomly selected apps from our dataset for typestate errors and violations of internal constraints. We did not check for unsatisfied predicates or forbidden events because these are hard to detect manually. We compare the results of our manual analysis to those reported by COGNICRYPT\textsubscript{AST}. Our goal here is to compute precision and recall of the analysis implementation in COGNICRYPT\textsubscript{AST}. Not the quality of our CrySL rules. We discuss the latter in Section 7.4. Consequently, we define a false positive to be a warning that should not be reported according to the specified rule, irrespective of that rule’s semantic correctness (similarly for false negatives).

Results. In the 50 apps we inspected, COGNICRYPT\textsubscript{AST} detects 228 usages of JCA classes. Table 1 lists the misuses it finds. Overall, the analysis finds 156 misuses. In particular, it issues 27 typestate-related warnings, with only 2 false positives, because the analysis is path insensitive (Section 5). We further found 4 false negatives, which are caused by initializing a MessageDigest or a MAC object without completing the operation. COGNICRYPT\textsubscript{AST} fails to find these typestate errors, because the supporting alias analysis times out, and COGNICRYPT\textsubscript{AST} aborts the typestate analysis without reporting a warning.

The automated analysis finds 129 violations of internal constraints. We were able to confirm 110 of them. For the other 19 cases, the analysis fails to statically extract possible runtime values for certain variables due to obfuscated code. For such values, the constraint solver reports the corresponding constraint as violated. We have also checked the apps for missed constraint violations, but were not able to locate any.

| Total Warnings | False Pos. | False Neg. |
|----------------|------------|------------|
| Typestate      | 27         | 2          | 4          |
| Constraints    | 129        | 19         | 0          |
| Total          | 156        | 21         | 4          |

RQ1: Our manual analysis shows that our typestate analysis achieves high precision (92.6%) and recall (86.2%). The constraint resolution has a precision of 85.3% and a recall of 100%.

7.2 Types of Misuses (RQ2)

Setup. We report the results of analyzing all 10,001 Android apps from AndroZoo. We then use the results of our manual analysis (Section 7.1) as a baseline to evaluate our findings on a large scale.

Results. COGNICRYPT\textsubscript{AST} detects the usage of at least one JCA class in 4,071 apps (41% of the analyzed apps). Most of these apps (96%) contain at least one misuse. In total, COGNICRYPT\textsubscript{AST} discovers 19,756 individual object traces that contradict the specified rule patterns. We categorize these misuses into the following: typestate errors (2,669), unsatisfied predicates (3,523), forbidden events (159), and internal constraint violations (11,436).

The violations of internal constraints represent the largest class of misuses. Approximately 82% of these violations are related to MessageDigest. In our manual analysis, most violations (89/110) originate from usages of MD5 and SHA-1. Many developers still use these algorithms, although both are no longer recommended by security experts [14]. COGNICRYPT\textsubscript{AST} identifies 1,766 (15.4%) constraint violations related to Cipher usages. Our manual analysis confirms that all misuses of the Cipher class are due to using the insecure algorithm DES or mode of operation ECB. This result is in line with the findings of prior studies [11, 12, 27].

More than 75% of the typestate errors are caused by misuses of MessageDigest. Through our manual analysis, we attribute this high number to incorrect usages of reset. In addition to misusing MessageDigest, misuses of Cipher contribute 421 typestate errors. Finally, COGNICRYPT\textsubscript{AST} detects 89 typestate errors related to PBEKeySpec. The ORDER section of the CrySL rule for PBEKeySpec requires calling clearPassword at the end of the lifetime of a PBEKeySpec object. We manually inspected 3 of the reported misuses and observed that the invocation of clearPassword is missing in all of them.

Predicates are unsatisfied when COGNICRYPT\textsubscript{AST} expects the interaction of multiple object traces but is not able to prove their correct interaction. With 3,523 unsatisfied predicates reported, the number may seem relatively large because unsatisfied predicates accumulate transitively. For example, if COGNICRYPT\textsubscript{AST} cannot ensure a predicate for a usage of IVParameterSpec, it will not generate a predicate for the key object that KeyGenerator generates using the IVParameterSpec object. Transitivity, COGNICRYPT\textsubscript{AST} reports an unsatisfied predicate for a Cipher object that relies on the generated key object.

COGNICRYPT\textsubscript{AST} also finds 159 calls to forbidden methods. As only two JCA classes require the definition of forbidden methods in our CrySL ruleset (PBEKeySpec and Cipher), we do not find this low number surprising. A manual analysis of a handful of reports suggests that most of the reported forbidden methods originate from the insecure PBEKeySpec constructors (Section 3).

From the 4,071 apps that use at least one JCA Crypto API, 1,757 contain at least one typestate error (43%), 1,079 lack required predicates (26.5%), 155 use at least one forbidden method (3.8%), and 4,001 violate at least one internal constraint (93.7%). Ignoring the class MessageDigest, 1,119 apps still violate at least one constraint in other classes.

RQ2: 96% of apps misuse at least one Crypto API. Violating the constraints of MessageDigest is the most common type of misuse.

7.3 Performance (RQ3)

Setup. COGNICRYPT\textsubscript{AST} comprises four main phases. It constructs (1) a call graph using FlowDroid [5] and then runs the actual analysis (Section 5), which (2) calls the typestate analysis and (3) constraint analysis as required, attempting to (4) resolve all declared predicates. During the analysis of our dataset, we measured the execution time that COGNICRYPT\textsubscript{AST} spent in each phase. We ran COGNICRYPT\textsubscript{AST} once per application and capped the time of each run to 30 minutes.
We attribute this to two main reasons. First, apps have different

with the typestate analysis having a median runtime of 3.2 seconds.

cates in hence, can be modelled using only internal constraints and pre-

the original rules takes approximately 0.6 seconds for half of the ap-

30,259 (median: 3,075 methods). The majority of the total analysis

Cr/ySL Call Graph
Total Time
Predicate
Typestate
Constraints

Figure 11: Performance of CogniCryptSAST.

Results. Overall, CogniCryptSAST times out after 30 minutes for
only 275 of all 10,001 apps in our dataset (2.75%). Unfortunately, CogniCryptSAST crashed during the analysis of 604 apps in dif-
ferent phases. Figure 11 summarizes the distribution of analysis
times (in seconds) for the four phases as well as the total analysis
time. The numbers are reported across the remaining 9,122 apps
for which the analysis successfully terminates in the allotted 30
minutes. For each phase, the box plot highlights the median, the
25% and 75% quartiles, and the minimal and maximal values of the
distribution.

Across the apps in our dataset, there is a very large variation in
the reported execution time (between 10 seconds and 29.9 minutes).
We attribute this to two main reasons. First, apps have different
sizes—reachable methods in the call graph vary between 141 and
30,259 (median: 3,075 methods). The majority of the total analysis
time is spent on call-graph construction. Resolving all declared
predicates takes approximately 0.6 seconds for half of the apps,
with the typestate analysis having a median runtime of 3.2 seconds.
For more than half of the apps, the value extraction and constraint
resolution finishes in less than 1 second.

RQ3: On average, CogniCryptSAST analyzes an app in 108 seconds,
with call-graph construction taking most of the time (76%).

7.4 Comparison to Existing Tools (RQ4)

Setup. We compare CogniCryptSAST to CryptoLint [12], the
most closely related tool. Unfortunately, we were unable to ob-
tain access to CryptoLint’s implementation, despite contacting
the authors. However, we were able to use CrySL to reimplement
the original ruleset of CryptoLint. CrySL has generally proven
expressive enough to model the CryptoLint rules, proving it is a
useful specification language beyond the scope of this work.

Our original CrySL ruleset covers all JCA classes. CryptoLint,
however, comprises only six individual rules. For easier distinc-
tion, we refer to our full ruleset for all JCA classes as RULESETCL,
the original rules CryptoLint uses as RULESETCL, and our CrySL
version for them as RULESETCLCrySL. Both RULESETCL and RULE-
SETCLCrySL are available at our project website. RULESETCL does
not include any typestate properties or forbidden methods, and
hence, can be modelled using only internal constraints and pre-
dicates in CrySL. For three out of the six rules in RULESETCL, CrySL
expresses exactly the checks that CryptoLint performs. The re-
mainng three rules (3, 4, and 6 in [12]) cannot be directly expressed.

CryptoLint rule 4, for instance, requires non-constant values for
salts in PBEKeySpec. In CrySL such a relationship is expressed
through predicates. However, predicates model correct behaviour
only. Therefore, in CrySL we had to further strengthen this Cryp-
toLint rule: we created a rule for PBEKeySpec that requires the
salt to be random. We followed a similar approach with the other
two rules in RULESETCL. Despite being more strict than RULESETCL,
RULESETCLCrySL ensures a fair comparison between CogniCryptSAST
and CryptoLint: when comparing the two tools in terms of their
findings, the stricter rules in RULESETCLCrySL tend to produce more
warnings than RULESETCL, which works in favor of CryptoLint.

Results. Using RULESETCLCrySL, CogniCryptSAST detects usages
of JCA classes in 1,726 Android apps. In total, it reports 6,098 mis-
uses, only a third of roughly 20,000 misuses that CogniCryptSAST
identifies using the RULESETCL. For each of the four types of mis-
uses, CogniCryptSAST finds more apps using RULESETCL. Using
RULESETCLCrySL, all reported warnings are related to 6 classes, com-
pared to 14 using RULESETCL. The differences mainly stem from
three types of uses. As we have pointed out, RULESETCLCrySL does not specify any typestate properties or forbidden methods.
Hence, it does not find approximately 3,000 warnings that Cog-
niCryptSAST identifies in these categories using RULESETCL. Fur-
thermore, while CogniCryptSAST reports 11,436 constraint viola-
tions using RULESETCL, it reports only 1,356 using RULESETCLCrySL.

To our surprise, significantly fewer apps violate four of the six
original rules in RULESETCL. For example, for CryptoLint rule 1
that forbids the use of ECB mode for encryption, CryptoLint iden-
tified 7,656 apps breaking this rule (62.5% of apps that use Crypto
APIs). Using RULESETCLCrySL, CogniCryptSAST identifies 658 usages
of ECB mode in 38.1% of apps that use Crypto APIs. Although a high
number of apps still exhibit this basic misuse, there is a consider-
able decrease compared to previous studies.

RQ4: The more comprehensive CogniCryptSAST ruleset detects 3×
as many misuses as CryptoLint in twice as many JCA classes.

7.5 Threats to Validity

Our ruleset is mainly based on the documentation of the JCA [24].
Although the authors of this paper have significant domain ex-
terise, our CrySL-rule specifications for the JCA are only as correct
as the JCA documentation. Our static analysis toolchain depends
on multiple external components. Yet, of course, we cannot fully
rule out bugs in the implementation.

Java allows a developer to programatically select a non-default
cryptographic service provider. CogniCryptSAST currently does
not detect such customizations but instead assumes that the default
provider is used. This behaviour may lead to imprecise results,
because our rules forbid certain default values that are insecure for
the default provider but may be secure for a different one.

8 RELATED WORK

In this section, we discuss languages that specify API properties
and tools that detect misuses of security APIs.

Specifying API Properties. There is a significant body of research
on textual specification languages that ensure API properties by

means of static data-flow analysis. For example, tracematches [2] enable runtime-checking typestate properties defined by regular expressions over runtime objects. Bodden et al. [8, 10] as well as Naeem and Lhoták [23] present algorithms to (partially) evaluate state matches prior to the program execution, using static analysis.

Martin et al. [19] present Program Query Language (PQL) that enables a developer to specify patterns of event sequences that constitute potentially defective behaviour. A combination of static and dynamic analyses match the patterns to a given program. A pattern may include a fix that is applied to each match by dynamic instrumentation. PQL has been applied to detecting security-related vulnerabilities such as memory leaks [19], SQL injection and cross-site scripting [18]. Compared to tracematches, PQL captures a greater variety of pattern specifications, at the disadvantage of using a flow-insensitive static analysis. PQL serves as the main inspiration for the CrysYl syntax. Other languages that pursue similar goals include PTQL [15], PDL [21], and TSJf [9].

These languages and their analysis-tool support are different from CrysYl and CogniCryptSAST in three main aspects. First, these systems follow a black-list approach by defining and finding incorrect program behaviour. On the other hand, CrysYl rules define desired behaviour, which in the case of Crypto APIs leads to more compact specifications. Second, the above languages are general-purpose languages for bug finding, while CrysYl specifically targets misuses of Crypto APIs, which may seem a limitation of CrysYl. However, the stronger focus on cryptography allows us to cover a greater portion of cryptography-related problems in CrysYl compared to other languages, while at the same time keeping CrysYl relatively simple. Third, CogniCryptSAST uses state-of-the-art static analyses that have superior performance and precision compared to other static-analysis approaches [28].

Detecting Misuses of Security APIs. Throughout the paper, we have discussed CryptoLint [12], and compared it to CogniCryptSAST in Section 7. Another tool that finds misuses of Crypto APIs is Crypto Misuse Analyzer (CMA) [27]. The CMA ruleset has significant overlaps with our CrysYl ruleset. However, the CMA rules are limited to misuses related to encryption and hashing. Unlike CogniCryptSAST, CMA has been evaluated on a small dataset of only 45 apps. Chatzikontstantinou et al. [11] ran a dynamic checker for a number of misuses and manually verified their findings on 49 apps. All three studies concluded that at least 88% of the studied apps misuse at least one Crypto API.

Unlike CogniCryptSAST, none of these tools facilitates rule creation by means of a higher-level specification language. Instead, the rules are hard-coded into the tool, making it hard for non-experts to extend or alter the ruleset. Due to its Java-like syntax, CrysYl enables regular developers—including cryptography experts—to define their own rules. CogniCryptSAST then automatically transforms those rules into the appropriate static analysis checks. Finally, CogniCryptSAST includes a typestate analysis that checks for generally forbidden methods.

9 CONCLUSION
In this paper, we present CrysYl, a description language for correct usages of cryptographic APIs. Each CrysYl rule is specific to one class, and it may include usage pattern definitions and constraints on parameter values. Predicates model the interactions between classes. For example, a rule may generate a predicate on an object if it is used successfully, and another rule may require that predicate from an object that it uses. We also present CogniCryptSAST, a static analyzer that checks a given program for its compliance with our CrysYl ruleset. Applying CogniCryptSAST to 10,001 Android apps, we found 20,000 misuses spread over 96% of the 4,071 apps that use the JCA. CogniCryptSAST terminates successfully in under 2 minutes for more than half of the apps.

In future work, we plan to address the following challenges. CrysYl currently only supports a binary understanding of security—a usage is either secure or not. We would like to enhance CrysYl to have a more fine-grained notion of security. This notion will allow for more nuanced warnings in CogniCryptSAST. This is challenging, because the CrysYl language still ought to be concise. Also, CrysYl currently requires one rule per class per JCA provider, because there is no way to express the commonality and variability between different providers implementing the same algorithms. This leads to specification overhead. To address this, we plan to modularize the language using import and override mechanisms. Moreover, we plan to consider extending CrysYl to support more complex properties such as using the same cryptographic key for multiple purposes. Finally, we plan to improve the performance of CogniCryptSAST through incremental static analysis [4].

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