Naturalistic Static Program Analysis

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Abstract—Static program analysis development is a non-trivial and time-consuming task. We present a framework through which developers can define static program analyses in natural language. We show the application of this framework to identify cryptography misuses in Java programs, and we discuss how it facilitates static program analysis development for developers.

Index Terms—Static program analysis, cryptography, natural language programming

I. INTRODUCTION

Static program analysis is the art of examining programs without requiring to execute the code. However, static analysis tools generate false positives and tuning them requires expertise. Likewise, program analysis development requires a deep knowledge of compiler or mastering an analysis framework.

End-user programming is a set of techniques that enable end users to write programs at a level of complexity that is adequate to their practices, background, and skills. For instance, it includes visual languages to program robots through visual blocks [1], and simplified programming languages to translate English sentences to Bash commands [2]. We believe that end-user programming techniques can also help to hide the complexity of writing a static program analysis task for nonprofessional programmers and empower them in this domain.

We introduce NASRA (NAturalistic Static pRogram Analysis), a framework that enables developers to define a program analysis task in natural language (NL), and it generates the corresponding Query Language (QL) query that underlies CodeQL program analysis engine.¹ We illustrate the application of this framework to find cryptography misuses in Java programs. NASRA is open source and publicly available.²

The ultimate goal of NASRA is to enable "naturalistic" static program analysis development in a way that developers can specify what they need without deep knowledge of static program analysis and how a specific framework works. Its higher level of abstraction than existing static analysis frameworks may facilitate a more intuitive formulation of program analysis tasks. Similarly, its agnostic nature to programming languages can provide a cross-language interface for program analysis, which obviates the need to learn the specifics of a program analysis framework. This paper presents a preliminary step to realize the above goal.

II. THE NASRA FRAMEWORK

Cryptography is an essential component to security, but it is one of the notorious topics where developers struggle a lot [3], [4]. Locating the init method invoked on a Cipher object is often deemed to be the first step to analyze cryptography code in Java programs. For instance, in CodeQL, one should write the following query to implement this task.

```
from MethodAccess init
where init.getMethod().getName() = "init" and
init.getReceiverType().getName() = "Cipher"
select init
```

We have developed a framework, called NASRA, that enables a more intuitive formulation of the above task in the form below:

An object of Cipher invokes init.

NASRA is a rule-driven synthesizer. We rely on predefined rules due to a lack of trustworthy labeled examples required for a data-driven approach in this domain. NASRA receives a program analysis inquiry in natural language, applies semantic parsing, and generates CodeQL commands. The input inquiry should comply with a subset of the syntax of Attempto Controlled English (ACE) controlled natural language. We use Attempto Parsing Engine (APE), a tool that receives a series of ACE statements and produces the corresponding Discourse Representation Structures (DRS) that is a semantic representation of the input text. NASRA applies the translation rules, explained later in this section, on the given DRS and produces the corresponding CodeQL statements. Thanks to APE, the way one can formulate NASRA statements is very flexible and there is no need for absolute correspondence with the NASRA syntax. We chose CodeQL as our code analysis engine because it is an industry-leading and communitypowered tool, and its publicly available to all GitHub users without any installation hassle. To employ NASRA for a new static analysis framework, only the transformation rules have to be adapted. To support a new application domain, we should identify the types of queries that the current syntax does not support, add the corresponding production rules to the syntax, and develop translations for them. NASRA is open source, and currently, supports program analysis tasks that concern cryptography misuses in Java programs.

¹https://codeql.github.com

²https://doi.org/10.5281/zenodo.7495044

A. Syntax and Semantics

Each NASRA query comprises one or more Statement. The syntax is shown below (terminals have different color).

$Query ::= Statement Query \mid Statement$
$Statement ::= BasicStatement \mid LogicalStatement$
Extension
BasicStatement ::= Exp is (Exp in List)
Exp ::= Prefix Exp type ID Literal
$Prefix ::= ((adjective \varepsilon) attribute of)$
LogicalStatement ::= Statement and Statement
Statement or Statement It is false that Statement
If Statement then Statement

a) Expression: The smallest building block is **Exp**. It includes a Literal (String or int) or an ID (user defined identifier) that are directly mapped to CodeQL expressions. An Exp can also be a CodeQL type such as class, variable, and method access that are mapped to Class, Variable, and MethodAccess, respectively.

b) Prefix: Each Exp can have an optional **Prefix** in the form of "*attribute of*" that indicates an attribute of the expression. For instance, name, type, argument, and method are attributes of an entity (*i.e.*, Exp), and they correspond to getName(), getType(), getArgument(), and getMethod() methods in CodeQL, respectively.

For example, "name of method1" is an Exp, where "name" is an attribute and method1 is an ID, and the whole expression is translated to method1.getName() in CodeQL.

Additionally, the attribute itself can have an optional ordinal number as an *adjective*, like *second* in the Exp "second argument of init" that is translated to "init.getArgument(1)", where second is translated to 1 as an argument according to zero-based numbering.

Note that "attribute of" can be repeated several times, where each attribute may have an adjective. For example, the Exp "The type of the second argument of init" has one ID (*i.e.*, init) and two attributes (*i.e.*, type and argument).

c) Basic Statement: Each **BasicStatement** is a statement that can serve as a Boolean condition as well as an assumption.

As a *Boolean condition*, BasicStatement produces equivalence of two Exps, as well as membership of an Exp in a list. In "Exp is Exp" structure, both sides of equivalence are Exps and they need to be equal, while in "Exp is in List" structure, the Exp needs to be equal to an item in a list. Accordingly, a statement like "arg1 is in ["RSA", "AES"]." is a disjunctive expression and can be rephrased to "arg1 is "RSA" or arg1 is "AES".", that is ultimately translated to "arg1 = "RSA" or arg1 = "AES"".

The syntax structure *Exp* is *Exp* can also produce *as*sumptions when the second Exp is a CodeQL type. The assumptions are mapped to the from part of a CodeQL query. For instance, the statement "var1 is a variable." translates to "Variable var1" and belongs to the from part.

d) Logical Statement: A LogicalStatement can be a negation, conjunction, disjunction, or implication. For example, "If arg1 is "RSA" then arg2 is "AES"." is translated to

"not (arg1 = "RSA") or arg2 = "AES"" in CodeQL, since $p \Rightarrow q$ is equivalent to $\neg p \lor q$.

B. Extensibility

One can extend NASRA to cover auxiliary statements and statement patterns. Their corresponding production rules are as follows.

$Extension ::= Pattern \mid .$	AuxiliaryStatement
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We introduce these features through three statement patterns and one auxiliary statement that are helpful to cover constraints on using Java cryptography objects.

1) Patterns: We present three patterns that extend **Pattern** nonterminal in the syntax. We discuss each in the following.

a) Invocation: We use this pattern to state that a method is *invoked by* an instance of a specific class. It can also be used to make sure that there is *no invocation* of a method by any instance of a specific class.

 $Pattern_1 ::= An object of ID$ (invokes does not invoke) ID.

The NASRA query shown in Section II is an example of this pattern. The transformation follows a number of steps. First, a MethodAccess is declared with the same name used in the NASRA statement (*i.e.*, init). Then the conditions need to be added to the where part. Specifically, the name of the method of the MethodAccess init should be "init" that is stated in the second line. Finally, a MethodAccess has a receiver, that is the object invoking its method. In this case, the name of the type of the receiver should be "Cipher", that is expressed in CodeQL in the third line.

If one needs to make sure that *no invocation* occurs, an existential quantifier must be used, as shown in the following.

```
from
where not (exists (MethodAccess init |
init.getMethod().getName() = "init" and
init.getReceiverType().getName() = "Cipher"))
```

It means that there is no such MethodAccess init that has these conditions. We can state this in NASRA in the form below.

An object of Cipher doesn't invoke init.

b) Partial order constraints: This pattern enables one to put partial order constraints on method invocations. In other words, one can enforce a method invocation to be preceded (or followed) by another method invocation.

Pattern2::=MethodName (precedes|follows) MethodName.

For example, there are two steps in CodeQL for stating that "invocation of getInstance is earlier than invocation of init". First, one should specify that both methods are in the same scope. Next, the line number of the preceding method invocation has to be smaller than the line number of the other method invocation. This is shown below.

<pre>getInstance.getEnclosingCallable()</pre>	=
<pre>init.getEnclosingCallable() and</pre>	
<pre>getInstance.getLocation().getEndLine()</pre>	<
<pre>init.getLocation().getEndLine()</pre>	

We can express this query in NASRA as follows.

getInstance precedes init.

c) Method signature constraint: It is possible to express signature of a method using **Pattern**₃.

Pattern₃ ::= MethodName's signature is List.

A method signature can be seen as an ordered list of data types. This list contains names of data types as strings, such that the first string is the name of the first argument's data type and so on. For example, the following NASRA query states that getInstance method has two arguments and the names of their types are "int" and "Certificate", respectively.

getInstance's signature is ["int", "Certificate"].

This query is translated to the following CodeQL query.

```
(count (getInstance.getAnArgument()) = 2) and
getInstance.getArgument(0).getType().
toString()="int" and getInstance.
getArgument(1).getType().toString()=
"Certificate"
```

First, the number of arguments is set to the size of the user defined list, then the type of arguments are constrained one by one. count (method.getAnArgument()) returns the number of arguments of the method.getArgument(i) returns the argument number *i* in the given method, getType() returns the type of the given argument, and finally toString() converts the given data type to a String.

2) AuxiliaryStatement: We aim to find misuses in code that violate one or more mandatory constraints. For instance, suppose that if the second argument of init method is "private key" then it is mandatory that the encryption algorithm, *i.e.*, the second argument of getInstance method is "RSA", and also if the encryption algorithm is "AES" then it is mandatory that the mode of encryption, *i.e.*, the first argument of the getInstance method, is "CBC". The following NASRA query will find such violations.

```
It is false that if the type of the second argument of init
is "PrivateKey", then the algorithm of getInstance's
first argument is "RSA" or it is false that if the algorithm of
getInstance's first argument is "AES" then the mode of
getInstance's first argument is "CBC".
```

In order to find any violation of these constraints, disjunction of their negation has to be stated in the query.³ Nevertheless, the above statement becomes much longer and harder to comprehend as the number of constraints increases.

We define *auxiliary statements* to ease the formulation as well as the comprehension of complex queries for developers. Particularly, **NecessityStatements** are auxiliary statements that enable developers to enforce mandatory constraints in short and independent statements. It starts with "*It is necessary that*" and follows the syntax below.

Necess	sityStatement	::=
It is	necessary that <i>Statement</i> .	

Therefore, instead of writing disjunction of negation of all constraints in one single statement, developers can benefit this construct (i.e., NecessiyStatement) to define all such constraints in several statements within a query. Accordingly, the single but long previous statement can be stated as two separate statements shown below.

It is necessary that if the type of the second argument of init is
"PrivateKey", then the algorithm of getInstance's first
argument is "RSA".
It is necessary that if the algorithm of getInstance's first
argument is "AES" then the mode of getInstance's first
argument is "CBC".

Necessity statements are treated differently from other statements. If there is only one NecessityStatement, its enclosing statement is negated and added to the where part of the CodeQL query. If there are more than one, *e.g.*, *n* constraints $Cons_1$, $Cons_2$, ..., $Cons_n$, then the "(not $TCons_1$ or not $TCons_2$ or ... or not $TCons_n$)" will be added to the where part, where $TCons_i$ is the translation of $Cons_i$.

III. WORKING EXAMPLES

Cipher is one of the most misused APIs in Java cryptography [4]. Listing 1 shows how to create a Cipher object in Java. We should call the Cipher's getInstance method. This method receives a number of arguments. The first one is transformation that is a string containing three parts separated by "/". These parts are algorithm, mode, and padding, respectively. Next, we should call the init method on the cipher object with two arguments to indicate the operation mode of the cipher, and to initialize this object with a Key or Certificate.

Cipher cipher = Cipher.getInstance("AES/ECB/
PKCS5Padding");
<pre>cipher.init(Cipher.ENCRYPT_MODE, new SecretKeySpec(</pre>
<pre>keyBytes, "AES"));</pre>

```
Listing 1. Setting up the Cipher object in Java
```

In the rest of this section, we present three different program analysis tasks to ensure secure use of Java Cipher.

A. Key vs. Algorithm

Task 1: If the key has a type of PublicKey, PrivateKey, or Certificate, or encryption mode is WRAP_MODE or UN-WRAP_MODE, then algorithm of transformation must be "RSA".

³For example, in "X is driving in an urban area($Cond_1$). It is necessary that X is driving slower than 60 km/h ($Cons_1$). It is necessary that X fastens the seat belt ($Cons_2$).", the query needs to find an X that is driving in an urban area and is driving faster than 60 km/h or is not using the seat belt. If we assign a Boolean variable to each statement as mentioned in the statements, it should aim $Cond_1 \wedge (\neg Cons_1 \vee \neg Cons_2)$ whose necessity part is translated to the disjunction of negation of two constraints.

Listing 2 shows how to check this constraint in CodeQL.

```
from MethodAccess getInstance, MethodAccess init
where init.getMethod().getName() = "init" and init.
getReceiverType().getName() = "Cipher" and
getInstance.getMethod().getName() = "getInstance"
    and getInstance.getReceiverType().getName() =
    "Cipher" and (((init.getArgument(0).toString() =
    "Cipher.WRAP MODE" or init.getArgument(0).
    toString() = "Cipher.UNWRAP MODE") or (init.
    getArgument(1).getType().toString() = "java.
    security.PublicKey" or init.getArgument(1).
    getType().toString() = "java.security.PrivateKey
    " or init.getArgument(1).toString() = "java.
    security.cert.Certificate")) and not(getInstance
    .getArgument(0).toString().replaceAll("\","").
    splitAt("/",0) = "RSA"))
select getInstance, init
```

Listing 2. Key vs. Algorithm constraint in CodeQL

This constraint can be expressed in NASRA as follows.

An object of Cipher invokes init. An object of Cipher invokes getInstance. It is necessary that if init's first argument is in ["Cipher.WRAP_MODE", "Cipher.UNWRAP_MODE"] or the type of the second argument of init is in ["PublicKey", "PrivateKey", "Certificate"] then the algorithm of getInstance's first argument is "RSA".

B. Algorithm vs. Transformation Mode

Task 2: If the algorithm of transformation is "RSA" then the mode of transformation must be either "" or "ECB".

Listing 3 shows the corresponding query to check this constraint in CodeQL. We should look for code in which the algorithm is "RSA", but neither "ECB" nor "" is set for the mode.

```
from MethodAccess getInstance
where getInstance.getMethod().getName() = "
    getInstance" and getInstance.getReceiverType().
    getName() = "Cipher" and (getInstance.
    getArgument(0).toString().replaceAll("\"","").
    splitAt("/", 0) = "RSA") and not (getInstance.
    getArgument(0).toString().replaceAll("\"","").
    splitAt("/", 1) = "" or getInstance.getArgument
    (0).toString().replaceAll("\"","").splitAt("/",
    1) = "ECB")
select getInstance
```

Listing 3. Algorithm vs. Transformation Mode constraint in CodeQL

This constraint can be expressed in NASRA as follows.

An object of Cipher invokes getInstance. It is necessary that if the algorithm of getInstance's first argument is "RSA" then the mode of getInstance's first argument is in ["", "ECB"].

Thanks to Attempto Parsing Engine (APE), NASRA statements do not need to exactly follow the syntax rules meaning that a degree of freedom in paraphrasing is possible. For instance, the part "the algorithm of getInstance's first argument is "RSA"" can also be written in two other forms:

(i) the algorithm of the first argument of getInstance is "RSA".(ii) "RSA" is the algorithm of getInstance's first argument.

C. Transformation and Encryption Mode vs. Signature

Task 3: If the transformation mode is either of "CBC", "PCBC", "CTR", "CTS", "CFB", or "OFB", and the encryption mode is not "Cipher.ENCRYPT_MODE", then the invoked init method should not have any of the following signature: init(encmode, cert), init(encmode, cert, ranGen), init(encmode, key), init(encmode, key, ranGen).

Listing 4 presents how to enforce this constraint in CodeQL.

```
from MethodAccess getInstance, MethodAccess init
where init.getMethod().getName() = "init" and init.
    getReceiverType().getName() = "Cipher" and
    getInstance.getMethod().getName() = "getInstance
    and getInstance.getReceiverType().getName() =
    "Cipher" and ((getInstance.getArgument(0).
    toString().replaceAll("\"", "").splitAt("/", 1) =
     "CBC" or getInstance.getArgument(0).toString().
    replaceAll("\"","").splitAt("/", 1) = "PCBC" or
    getInstance.getArgument(0).toString().replaceAll
    ("\"","").splitAt("/", 1) = "CTR" and
    getInstance.getArgument(0).toString().replaceAll
    ("\"","").splitAt("/", 1) = "CTS" or getInstance
    .getArgument(0).toString().replaceAll("\"","").
    splitAt("/", 1) = "CFB" or getInstance.
    getArgument(0).toString().replaceAll("\"","").
    splitAt("/", 1) = "OFB") and not (init.
    getArgument(0).toString() = "Cipher.ENCRYPT_MODE
    ")) and ((count (getInstance.getAnArgument()) =
    2 and getInstance.getArgument(0).getType().
toString() = "int" and getInstance.getArgument
    (1).getType().toString() = "Certificate") or (
    count (getInstance.getAnArgument()) = 3 and
    getInstance.getArgument(0).getType().toString()
    = "int" and getInstance.getArgument(1).getType()
    .toString() = "Certificate" and getInstance.
    getArgument(2).getType().toString() =
    SecureRandom") or (count (getInstance.
    getAnArgument()) = 2 and getInstance.getArgument
    (0).getType().toString() = "int" and getInstance
    .getArgument(1).getType().toString() = "Key") or
     (count (getInstance.getAnArgument()) = 3 and
    getInstance.getArgument(0).getType().toString()
    = "int" and getInstance.getArgument(1).getType()
    .toString() = "Key" and getInstance.getArgument
    (2).getType().toString() = "SecureRandom"))
select init, getInstance
```

Listing 4. Transformation and Encryption mode vs. Signature constraint in $\ensuremath{\mathsf{CodeQL}}$

The implementation of this task in NASRA is shown below.



D. Discussion

Table I presents the number of *distinct* operators and operands (*i.e.*, vocabulary), and the total number of operators and operands (*i.e.*, length) needed for each analysis task.⁴

⁴In NASRA, we consider user defined terminals such as init, "RSA", and getInstance as operands and count the rest of language constructs as operators.

Analysis Task	Vocabulary		Length	
Analysis Task	CodeQL	NASRA	CodeQL	NASRA
Key vs. Algorithm (III-A)	32	19	179	39
Algorithm vs. Mode (III-B)	27	18	107	24
Mode vs. Signature (III-C)	42	26	434	56

TABLE I CodeQL vs. NASRA

Evidently, queries in NASRA are significantly shorter than queries in CodeQL (*i.e.*, up to 87% reduction in length), and they consume a lot fewer programming constructs (*i.e.*, up to 38% fewer vocabularies). We computed Halstead complexity measures to estimate the coding time and the difficulty to write or understand these queries [5]. The results showed that developers require a lot less effort and time to develop these tasks in NASRA than in CodeQL.

We also asked ten developers to share their opinion about queries in NASRA. They unanimously stated that they are succinct and easy to understand, and one commented that *"these queries read like API documentation"*.

It is noteworthy that NASRA's performance, *i.e.*, how well it can detect API misuses, depends on its underlying analysis framework which is currently CodeQL. In other words, NASRA obviates the low-level details needed to define static program analyses, but the issues with false positives remain to be relevant. Moreover, despite being natural, the use of NASRA still requires knowledge of its syntax.

IV. RELATED WORK

Mapping a natural language statement into a formal representation has received great attention in the community but not much in the program analysis development domain.

Schlegel et al. developed an end-user programming paradigm for Python, that maps natural language commands into Python code [6]. Landhauber et al. proposed a domain agnostic command interpreter that receives natural language commands in English and uses ontology to produce relevant API calls [7]. Yaghmazadeh et al. developed SQLIZER, a system to automatically synthesize SQL queries from a natural language [8]. Luo et al. investigated the translation from a natural language query to visualization with the goal of simplifying the creation of data visualizations [9].

Heyman et al. developed a Python code completion tool that enriches developers' code with the natural language description of the intended data science task [10]. Nguyen et al. presented an approach that takes as input an English description of a programming task and synthesizes the corresponding API code template for the task [11]. Desai et al. built a general framework for constructing program synthesizers that take natural language inputs and produce expressions in a target Domain Specific Language [12]. Zhai et al. proposed a search-based technique to automatically translate NL comments to formal program specifications that specify the expected pre and post conditions [13].

The work presented in this paper is also related to cryptography domain. There exist tools that find cryptography misuses [14] and libraries that facilitate the adoption of cryptography for developers [15]. Nevertheless, none of them employed a natural language approach.

V. CONCLUSION

We introduced NASRA, an open-source framework to define static program analyses in natural language. We demonstrated the application of this framework to find misuses in Java cryptography. The ultimate goal of NASRA is to enable a naturalistic way to develop static program analyses, which is usable for mainstream developers. To realize this goal, further studies are needed to determine NASRA's effectiveness in real-world settings. The expressiveness of its queries and the effort required to extend it to other problem domains have to be investigated as well. Finally, automatic translation without pre-defined rules is also an exciting future research direction.

REFERENCES

- E. Barakova, J. Gillesen, B. Huskens, and T. Lourens, "End-user programming architecture facilitates the uptake of robots in social therapies," *Robotics and Autonomous Systems*, vol. 61, no. 7, 2013.
- [2] X. V. Lin, C. Wang, L. Zettlemoyer, and M. D. Ernst, "NL2Bash: A corpus and semantic parser for natural language interface to the linux operating system," in *Proceedings of the Eleventh International Conference on Language Resources and Evaluation (LREC 2018)*, 2018.
- [3] M. Hazhirpasand, O. Nierstrasz, M. Shabani, and M. Ghafari, "Hurdles for developers in cryptography," in 2021 IEEE International Conference on Software Maintenance and Evolution (ICSME), 2021, pp. 659–663.
- [4] M. Hazhirpasand, M. Ghafari, and O. Nierstrasz, "Java cryptography uses in the wild," in *Proceedings of the 14th ACM / IEEE International* Symposium on Empirical Software Engineering and Measurement, 2020.
- [5] M. H. Halstead, Elements of Software Science (Operating and programming systems series). Elsevier Science Inc., 1977.
- [6] V. Schlegel, B. Lang, S. Handschuh, and A. Freitas, "Vajra: Step-bystep programming with natural language," in *Proceedings of the 24th International Conference on Intelligent User Interfaces*, 2019.
- [7] M. Landhäuber, S. Weigelt, and W. F. Tichy, "Nlci: A natural language command interpreter," *Automated Software Engg.*, vol. 24, no. 4, p. 839–861, dec 2017.
- [8] N. Yaghmazadeh, Y. Wang, I. Dillig, and T. Dillig, "Sqlizer: Query synthesis from natural language," *Proc. ACM Program. Lang.*, vol. 1, no. OOPSLA, oct 2017.
- [9] Y. Luo, N. Tang, G. Li, J. Tang, C. Chai, and X. Qin, "Natural language to visualization by neural machine translation," *IEEE Transactions on Visualization and Computer Graphics*, vol. 28, no. 1, pp. 217–226, 2022.
- [10] G. Heyman, R. Huysegems, P. Justen, and T. Van Cutsem, "Natural language-guided programming," ser. Onward!, 2021, p. 39–55.
- [11] A. T. Nguyen, P. C. Rigby, T. Nguyen, D. Palani, M. Karanfil, and T. N. Nguyen, "Statistical translation of english texts to api code templates," in 2018 IEEE International Conference on Software Maintenance and Evolution (ICSME), 2018, pp. 194–205.
- [12] A. Desai, S. Gulwani, V. Hingorani, N. Jain, A. Karkare, M. Marron, S. R, and S. Roy, "Program synthesis using natural language," in *Proceedings of the 38th International Conference on Software Engineering*, ser. ICSE '16, 2016.
- [13] J. Zhai, Y. Shi, M. Pan, G. Zhou, Y. Liu, C. Fang, S. Ma, L. Tan, and X. Zhang, "C2s: Translating natural language comments to formal program specifications," in *Proceedings of the 28th ACM Joint Meeting* on European Software Engineering Conference and Symposium on the Foundations of Software Engineering, ser. ESEC/FSE 2020, 2020.
- [14] Y. Zhang, M. M. A. Kabir, Y. Xiao, D. D. Yao, and N. Meng, "Automatic detection of java cryptographic api misuses: Are we there yet," *IEEE Transactions on Software Engineering*, 2022.
- [15] S. Kafader and M. Ghafari, "Fluentcrypto: Cryptography in easy mode," in 2021 IEEE International Conference on Software Maintenance and Evolution (ICSME), 2021, pp. 402–412.