Data flow analysis for Uranus applications

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December 12, 2020

Abstract

Trusted Execution Environments (TEE) protect applications from privileged attacks running on untrusted systems such as public clouds, but partitioning enclave boundaries is not always a trivial task. Partitions too small would leak data to the untrusted host system, while partitions too huge would result in unnecessarily large trusted computing base (TCB) that increases the risk of overflowing Enclave Page Cache (EPC). A passive analysis approach can be adopted where users annotate data as sensitive sources or sinks, and an analysis tool determines variables considered sensitive and compares it with the enclave boundaries declared.

This project introduces *enclavlow*, an information flow analysis tool for JVM-based projects using Intel SGX enclaves with the Uranus [1] framework. It implements a set of security policies tailored for Uranus-based applications, and reports leaking variables or functions that could be run out of enclave. The analysis tool is delivered as a Gradle plugin to be deployed as a continuous integration tool in Gradle-based projects. The source code for *enclavlow* is released on `https://github.com/SOF3/enclavlow`. The project work can be incorporated into Uranus in the future for optimizations.

[1] Uranus: Simple, Efficient SGX Programming and its Applications. `https://doi.org/10.1145/3320269.3384763`

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Abbreviations

3AC Three-Address Code

AFG Aggregate Flow Graph

API Application Programming Interface

AWS Amazon Web Services

CFG Contract Flow Graph

DTA Dynamic Taint Analysis

EPC Enclave Page Cache

JLS Java Language Specification

JNI Java Native Interface

JVM Java Virtual Machine

LFG Local Flow Graph

OOP Object-oriented Programming

SDK software development kit

SGX Software Guard Extension

TEE Trusted Execution Environment

1 Introduction

1.1 Background

With the rise of third-party public cloud services such as Amazon Web Services (AWS) [1] and Microsoft Azure [6], there is increasing demand for trusted execution where applications are protected from attackers with privileged access to the hardware or software. Modern hardware offer Trusted Execution Environment (TEE) technologies, such as Software Guard Extension (SGX) in Intel CPUs, with which trusted execution code and sensitive data are processed in secure "enclaves", protected at hardware level to prevent access from other hardware or software layers.

One significant application of TEE is in big data processing, where confidential user data are processed, and protection from cloud providers may be necessary for compliance with privacy regulations such as GDPR [8]. However, a significant subset of such applications are written using languages that use Java Virtual Machine (JVM) as the runtime, such as Hadoop [2] and Spark [3]. Recently, Uranus, a system for writing SGX applications in Java languages, was released [13]. It provides simple interface for SGX, where users annotate methods with `@JECall` and `@JOCall` to move control flow into or out of enclaves. It is the responsibility of the user to determine the correct positions for the `@JECall` and `@JOCall` annotations, namely the enclave boundary partitioning. Since JVM involves a different approach compared to native applications with software development and distribution, the tools applicable for native applications are mostly incompatible with JVM.

This project focuses on the dilemma of enclave boundary selection: running the whole application within an SGX enclave is undesirable for two reasons. First, this violates the Principle of Least Privilege, where the whole application becomes possible attack surface for adversaries to compromise protected data [14]. Second, this implies all memory used by the application is placed in the enclave memory (the Enclave Page Cache (EPC)), which is restricted to 100 MB before significant performance degrading ("1,000X slowdown compared to regular OS paging") [13]. On the other hand, if the enclave is smaller than necessary, adversaries can either obtain sensitive data directly or infer sensitive characteristics of them indirectly. An enclave boundary is to be selected with high precision to avoid either downside.

This project presents *enclavlow* [2], an information flow analysis tool for identifying data leak from enclaves. The user first wraps sensitive data sources in `sourceMarker` and sinks in `sinkMarker`. The tool performs information flow analysis from `sourceMarker` variables, identifying the ways that data from such variables are leaked to the system outside the executing enclave without first passing through a `sinkMarker` variable. The tool compiles a report in HTML format that summarizes the following:

- **Data leak**: The report displays the lines of code on which sensitive data are moved into areas accessible by privileged adversaries. It demonstrates the path from the `sourceMarker` expression to the point of leak.
- **Redundant protection**: The report lists the functions that could not hold any sensitive data in its local variables, hence should be moved out of the enclave partition.

[2] "enclavlow" is a new term coined from the words "enclave" and "flow".

enclavlow is shipped as a Gradle plugin, providing a Gradle task that takes the `*.class` files compiled in the `classes` task and generates the report for the analysis from those classes.

1.2 Prior work

Information flow analysis is not a new technology in the field. While this project analyzes JVM code using SGX enclaves, prior research on *automatic partition* and non-SGX dynamic analysis was found.

Glamdring [14] is a C framework that automatically selects the minimal SGX enclave boundaries based on user requirements specified through C pragma directives. However, since the process is fully automated, it has a lower tolerance of false positives, which increases the risk of unintentional data leak. This project, unlike Glamdring, will only perform analysis but not automatic partitioning, allowing for greater false positive tolerance.

Phosphor [9] is a Dynamic Taint Analysis (DTA) framework that modifies Java bytecode to add tags to sensitive data at runtime and check if such tags are leaked. Although dynamic taint is more accurate, this project prefers a static analysis approach, which enables developers to identify sensitive regions at compile time without the need to feed concrete data into methods.

Civet [10] is a framework for Java code partitioning. Similar to Glamdring, it automatically selects the minimal enclave boundaries. It is also similar to the goal of this project, except that Uranus provides additional protection at the native level, allowing further optimizations compared to Civet. Challenges found in this project, such as polymorphism complexity, were also observed with Civet.

This report will focus on the algorithm used to detect data leaks, as well as performance concerns and limitations from the JVM design.

2 Objectives

This section describes the usage and intended behaviour of *enclavlow*.

2.1 Marker API

The `enclavlow-api` Gradle submodule in the project is a library exposing two identity functions as expression markers as shown in Listing 1. Corresponding definitions such as `intSourceMarker` are also defined for the eight Java primitive types for both source and sink (omitted in Listing 1 for brevity). Users can wrap *ultimate* sensitive data sources with `sourceMarker` and mark *intended* leaks with `sinkMarker`.

Listing 1: Definition of `sourceMarker` and `sinkMarker`

```
1 package io.github.sof3.enclavlow.api;
2
3 public class Enclavlow {
4     public static <T> T sourceMarker(value: T) { return value; }
5
6     public static <T> T sinkMarker(value: T) { return value; }
7 }
```

Exceptions induced inside parameter expression for `sinkMarker` is not considered a sensitive data sink. This is because throwing sensitive data is a rare use case, has a wide range of scenarios and highly depends on the exact class thrown. If sensitive information in an exception is intended for leaking, a more verbose catch-wrap-throw syntax can be used as demonstrated in Listing 2. `sinkMarker` can also be used to explicitly suppress false positives generated by *enclavlow*.

Listing 2: Catch-wrap-throw construct

```
1 try {
2     thisMethodThrowsSensitiveExceptions();
3 } catch(SensitiveException e) {
4     throw sinkMarker(e);
5 }
```

A simple example usage is shown in Listing 3. In particular, on line 4, `raw` is not `sourceMarker` because parsing is a late stage after raw data extraction and `sourceMarker` should only be applied on the ultimate source, which is asserted on line 5 that "computing the sum of `raw` is a legitimate leak". `result` on line 14 is not marked `sinkMarker` because the leak of sensitive information should be analyzed. `sum` on line 22 is not marked `sinkMarker` because it is a sensitivity-neutral utility function that does not imply any assertion on whether the leak is acceptable; otherwise incorrect behaviour is created by changing line 12 to Listing 4, where `parse` no longer returns a security-sensitive value.

Listing 3: Simple example of `sourceMarker` and `sinkMarker`

```
1  class SourceSinkExample {
2      @JECall
3      int getSum(byte[] encrypted) {
4          List<Integer> raw = parse(encrypted);
5          return sinkMarker(computeSum(raw));
6      }
7
8      List<Integer> parse(byte[] encrypted) {
9          byte[] buf = sourceMarker(PRIVATE_KEY.decrypt(encrypted));
10         List<Integer> result = new ArrayList<>();
11         for(byte i : buf) {
12             result.add((int) i);
13         }
14         return result;
15     }
16
17     int computeSum(List<Integer> integers) {
18         int sum = 0;
19         for(int i : integers) {
20             sum += i;
21         }
22         return sum;
23     }
24 }
```

2.2 User interface

The `enclavlow-plugin` Gradle submodule is a Gradle plugin providing a task `:enclavlow`, which depends on the `:classes` builtin task and performs flow analysis on the class binaries. The analysis report is generated as HTML format at `build/reports/enclavlow/index.html` relative to the project on which task is invoked. The report contains the following elements:

Listing 4: Example of leak through `computeSum`

```
1 result.add(computeSum(Collections.singletonList((int) i)));
```

Method summary Each method defined in the source project (i.e. excluding libraries and Java software development kit (SDK)) is displayed with sensitive data that have passed through its parameters or return path. If multiple invocations lead to different data flows, the union of such data flows is displayed.

Redundant protection Methods detected to be run inside enclaves but never involved with any sensitive data are highlighted in an index called "Redundant protection". For each highlighted method, the developer should mark it as `@JOCall` to run out of enclaves or move its `@JECall` annotation to appropriate method calls, or adjust the `sourceMarker` / `sinkMarker` wrappers.

Data leaks Methods which result in immediate data leaks, such as methods passing security-sensitive data to other `@JOCall` methods or methods marked `@JECall` returning/throwing security-sensitive data, are highlighted in an index called "Data leaks". For each highlighted method, the developer should move it into enclave boundaries, or adjust the `sourceMarker` / `sinkMarker` wrappers.

2.3 Threat model

The adversary of concern has privileged access to the host system, including other threads in the JVM runtime, the JVM runtime itself, other (root) processes, the operating system kernel, the hypervisor, the BIOS and hardware such as the CPU and the RAM, with the exception of the SGX execution part of the CPU. Note that untrusted hardware cannot execute the enclave code in the presence of cryptographically provable attestation performed with Uranus [13], so privileged access to the CPU does not imply privileged access to the SGX module.

Since all applications of interest are run on Uranus, it is not meaningful to analyze threat models more capable than that as assessed by Uranus. In particular, side channels such as timing attacks are not to be assessed. *enclavlow* only studies attacks through at the data layer, where the adversary has read and write access to arbitrary data and instruction memory beyond SGX enclaves.

There are also some operating system-based exploits already tackled by Uranus. For example, system calls are intercepted by Uranus with secure mechanisms to ensure that control flow cannot be known by the system through these calls. Uranus also provides memory safety checks for object field assignment, but this check is disabled in this project since one of the goals is to provide a system that can be used to replace such check.

3 Methodology

The main component of this project is the analysis framework, which is conducted in the form of iterations to fulfill security policies as specified in the integration tests. Other parts such as Gradle plugin interfae, although necessary for usage, are not focus areas of this project, and hence will not be discussed further.

Table 1: Nodes in CFG

Static	Represents data located in static class fields
This	Represents the object on which a method was invoked
Param x	Each parameter is represented by a node
Return	Represents data flow through the return path
Throw	Represents data flow through the return path
Source	Represents variables in the method explicitly wrapped in `sourceMarker`
Sink	Represents locals in the method explicitly declared as `sinkMarker`
Control	This is a special node representing how many times the function is called.
This	Param y, Return, Throw and Control from each function called from the current node

3.1 Design

Since the adversary in the threat model has arbitrary access to any untrusted memory and instruction, the security policies of *enclavlow* differ slightly from typical information flow analysis. For instance, the statement `a.b.c = d;` usually does not propagate the effect of `d` to `a`, but since the adversary is capable of changing `b` to any memory location of its favour, the security of this statement depends on whether `a` is trusted.

enclavlow adopts a flow graph approach, where each node represents an element that may be leaked.

Definition 1. Given a flow graph (V, E), for all $x, y \in V$, $(x, y) \in E$ if and only if allocating y outside an enclave reduces the indistinguishability of x even if all other nodes are removed.

If the "even if" condition is removed, this is a transitive relation.

Note that this definition ("our definition") differs slightly from the usual definition of flow graphs (especially in DTA), where an edge (x, y) represents the flow of information from x to y [17]. In the usual definition, only adversary read access to y is concerned, while in our definition, the adversary possesses write access to x. *enclavlow* constructs flow graphs in three stages to reduce local opcodes to a cross-method flow graph.

3.1.1 Contract Flow Graph (CFG)

enclavlow constructs a CFG for each method analyzed. The CFG contains the nodes listed in Table 1. In this article, all flow graph nodes are underlined.

The CFG is computed by contracting the LFG, as described in the next subsection. After all methods in a class are evaluated, the CFGs of child methods called from the analyzed methods are lazily evaluated as well. All CFGs are merged into an Aggregate Flow Graph (AFG), joined using the function call nodes.

For the case of polymorphism in Object-oriented Programming (OOP), the CFGs of all overrides in scope are merged by taking the union of all flow edges. While it is possible to improve precision by performing call graph analysis to identify the exact subclasses passed to the method, it is not implemented in this

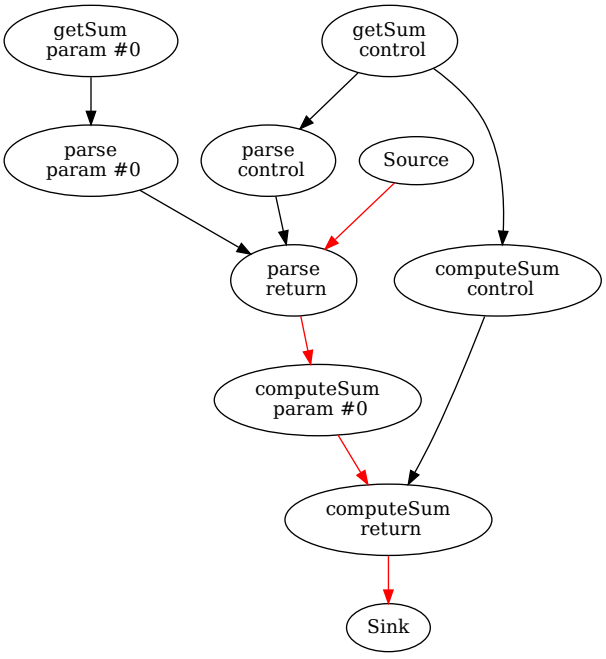
Table 2: 3AC instructions affecting LFG

Instruction type	Effects on LFG
Assignment	Control flows to lvalue nodes of destination. Erases current connections to lvalue nodes of destination. rvalue nodes of source flow to lvalue nodes of destination. lvalue nodes of source flow to rvalue nodes of destination.
Return	Control flows to Return node. rvalue nodes of returned value flow to Return node.
Throw	Control flows to Throw node. rvalue nodes of thrown value leaks to Throw node.
Conditional (If/Switch)	A new Control node is pushed to the control stack. Previous Control flows to the new Control. rvalue nodes of predicate leaks to the new Control.
Method call	Same effect as assigning call result to a sink variable.

project due to time constraints.

Figure 1 shows an example of AFG. Unconnected nodes are omitted for brevity.

Figure 1: Example CFG for Listing 3



3.1.2 Local Flow Graph (LFG)

To construct the CFG, a local flow graph is constructed to identify the information flow between temporary variables. The analysis follows along the control flow of the program, performing the *consume*, *branch* and *merge* operations.

The LFG extends the CFG with the following additions:

- Each local variable (some may only exist as intermediate values in source code) is allocated a node.
- Each branch has its own Control node.

The *consume* operation consumes statements in form of Three-Address Code (3AC) [12]. Every step adds or removes some flow edges, as described exhaustively in Table 2. The relationship between the graph and the "lvalue"s and "rvalue"s mentioned in Table 2 are explained in Table 3.

Table 3: lvalue and rvalue nodes for expressions

Expression type	lvalue nodes	rvalue nodes
Binary operations	unreachable	union of rvalues from operands
Array literal `new int[a]`	unreachable	union of rvalues from count
Array access `a[b]`	lvalues of `a`	rvalues of `a` and `b`
Instance field access `a.b`	lvalues of `a`	rvalues of `a`
Static field access `Class.field`	Static	none
Parameter	the parameter node [3]	the parameter node
Local variable	its own dedicated node	its own dedicated node
`this`	This	This
Class cast and instanceof	lvalues of the underlying value	rvalues of the underlying value
Method/constructor call	Return of the called method	Return of the called method

The *branch* operation performs a deep clone of the LFG and continues following each branch with its clone.

The *merge* operation pops the uppermost control flow node from the graph, and takes the union of all flows from each branched graph.

The control flow stack is always pushed from a conditional instruction before splitting into branches, which is the source of information leak for attacks that count the number of times a method was called.

Each node representing an object may contain subnodes that represent its fields. Edges to field nodes do not directly affect the parent object despite the intuitive belief that `a.b = c;` leaks `c` to `a`.

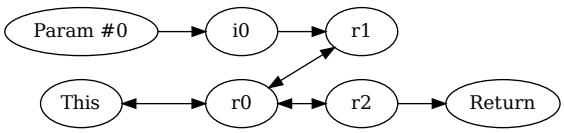
Listing 5: Iago attack

```
1  class IagoAttack{
2      Bar bar;
3      Qux qux;
4
5      Qux foo(int x) {
6          this.bar.x = x;
7          return this.qux;
8      }
9
10     static class Bar {
11         int x;
12     }
13
14     static class Qux {
15         int x;
16     }
17 }
```

In traditional information flow analysis, this naive approach described in the table appears to result in high false positive rate as it does not separate the internal structure used by instance fields and arrays. For example, consider Listing 5 (Jimple code in Listing 6). At return point, the LFG becomes as shown in Figure 2. Intuitively, this appears incorrect; param #0 does not flow to `return` since it is just used for `this.bar` but not `this.qux`. Nevertheless, in the threat model where the adversary has access to modify any memory allocated outside the enclave, such a program is vulnerable to Iago attacks [11], where assignment to object fields may not always work as intended; if the `IagoAttack` context was allocated outside the enclave, `this.bar` might be modified by the adversary to `this.qux` (even if they belong to different classes), hence leaking into the return value. Recall the definition of an edge in the LFG used in this project, where $(a, b) \in E$ implies b must to be protected if a is protected.

[3] Jimple always first assigns parameters to a local variable, so direct assignments to the parameter variable will not overwrite it.

Figure 2: LFG of `IagoAttack.foo(int)` in Listing 5



3.2 System Requirements

The logical code of this project is mostly implemented in Kotlin, a JVM language with more concise syntax than Java. However, to ensure that the behaviour analyzed is as explicit as possible, all test cases are written in Java.

As Uranus was only tested against Linux systems, this project does not intend to support other operating systems. Furthermore, due to classpath detection difficulties, only OpenJDK Version 8 and 11 are supported currently. Nevertheless, since *enclavlow* is just a developer tool, its runtime is actually independent of that targeted by Uranus, so it is possible to test support for other platforms in the future.

Listing 6: Iago attack (Jimple output)

```
1  class IagoAttack extends java.lang.Object
2  {
3      IagoAttack$Bar bar;
4      IagoAttack$Qux qux;
5      void <init>()
6      {
7          IagoAttack r0;
8          r0 := @this: IagoAttack;
9          specialinvoke r0.<java.lang.Object: void <init>()>();
10         return;
11     }
12     IagoAttack$Qux foo(int)
13     {
14         IagoAttack r0;
15         int i0;
16         IagoAttack$Bar $r1;
17         IagoAttack$Qux $r2;
18         r0 := @this: IagoAttack;
19         i0 := @parameter0: int;
20         $r1 = r0.<IagoAttack: IagoAttack$Bar bar>;
21         $r1.<IagoAttack$Bar: int x> = i0;
22         $r2 = r0.<IagoAttack: IagoAttack$Qux qux>;
23         return $r2;
24     }
25 }
```

enclavlow is packaged as a Gradle plugin, allowing developers to use it in projects with a Gradle toolchain. However, the `enclavlow-core` subproject can be reused in other contexts, such as Maven plugins, IDE plugins, etc.

3.3 Flow analysis framework

Soot [12] was selected as the framework for conducting flow analysis. Although multiple flow analysis systems using Soot already exist, they are not designed against SGX enclave protection, but *enclavlow* adopts more strict security policies to prevent attacks from more privileged attackers, unlike traditional information flow analysis that mostly detects user input as the source of insecurity.

Soot accepts Java bytecode files (`*.class`) as input and compiles them into a 3AC language called Jimple, which simplifies analysis work. The consume-branch-merge approach mentioned in the last subsection was inspired by the forward flow analysis interface in Jimple.

Other flow analysis frameworks were also considered, such as Joana [5] and JFlow [15]. Soot was chosen due to its distinctively thorough documentation and builtin support for call graph analysis.

3.4 Testing

This project uses JUnit 5 and `kotlin.test` framework to conduct both unit and integration tests. Test case classes are compiled together in the `:core:testClasses` task, which declares dependency on the APIs `sourceMarker` and `sinkMarker`.

4 Results and Discussion

There have been multiple unsolved difficulties and unimplemented features in this project, which can be tackled in future research.

4.1 Difficulties and Limitations

The principles of OOP imply that the receiver of a method call may be swapped with a compatible implementation in another subclass that performs different actions than the current one. Although Uranus prevents the adversary from passing arbitrary malicious code into the enclave memory, it is still possible to pass objects of unexpected trusted subclass through the `@JECall` boundary. Consider Listing 7 for example. If `cs` is passed with a `substr` implementation that writes its parameters to a static variable, the function would leak the length of the security-sensitive `secret`, which is not desirable. To correctly solve the vulnerability of OOP substitution, it is necessary to perform call graph analysis on the actual classes passed to the method, which involves more complex framework level work.

Listing 7: Example attack through OOP substitution

```
1  class OopSubstAttack {
2      @JECall
3      public void foo(CharSequence cs) {
4          byte[] secret = sourceMarker(new byte[0]});
5          writeEncrypted(cs.substr(secret.length()));
6      }
7  }
```

Despite optimizations and simplifications, it is still not possible to perform 100% accurate information flow analysis within efficient time complexity [16]. For example, this project merges conditional branches together by taking the union of flow graphs, resulting in easy false positive rates. Listing 8 is an example of this due to multiple return arms. The CFG contains an edge (`secret` $\rightarrow$ Return), but the returned value is in fact

Listing 8: Known false positives

```
1  class KnownFalsePositives {
2      int foo(int x) {
3          boolean secret = sourceMarker(1);
4          if (secret) {
5              return x;
6          } else {
7              return x;
8          }
9      }
10
11     static class Ref<T> {
12         T t;
13     }
14 }
```

always 1. This is not to be fixed since it is a minor use case; duplicated code in multiple return arms is typically regarded as an antipattern anyway.

It is also impossible to analyze further than the Java Native Interface (JNI) level, since analyzing across JNI boundary implies the need to interact with a native analysis tool. Since this involves multiple layers of interaction such as native code reverse engineering (hence legal issues) and platform-specific support (defeating the purpose of using JVM), Since Uranus effectively denies system calls, the contract is always assumed to be $\{(p, \text{return}) : p \in \text{params}\}$. This assumption might miss some special cases, such as the `System.arraycopy` method in the Java SDK, which leaks information about its bounds parameters to an array.

For the sake of consistency with Uranus, it was originally intended to expose `sourceMarker` and `sinkMarker` as annotations on local variables instead of method calls. However, Java Language Specification (JLS) 9.6.1.2 explicitly stated that "an annotation on a local variable declaration is never retained in the binary representation" [7], so a method call based approach is used instead. It is expected that JIT optimization removes the cost involved from an extra method call at JIT compile time.

4.2 Recommended future research

There are multiple areas in which this project can be extended.

enclavlow applies handwritten heuristics to identify leaks. Some special edges, such as field projection, are not very well-defined. This reduces the reliability of *enclavlow* in terms of robustness in targeted attacks, which is an important feature for security analysis. A formal proof through tools like Coq [4] can be utilized to ensure that the LFG construction does not miss marginal cases.

The project can also be used to improve Uranus performance. Currently, to ensure enclave confidentiality, Uranus requires enclave code accessing untrusted memory to use Uranus's untrusted-memory Application Programming Interface (API) like `SafeGetField` and `SafeWriteField` [13], which checks the memory address against enclave bounds at runtime. The static analysis in *enclavlow* allows Uranus to validate these bounds at compile time, hence avoiding the runtime bounds-checking cost and improve performance. Note that JIT optimization is not able to detect unnecessary bounds checking.

5 Conclusion

This project aims to develop a JVM code analysis tool for software using Uranus for SGX applications to assist the choice of enclave boundaries. A divide-and-conquer approach was adopted for efficient abstraction of information flow across a method. Since the project delivers an analysis tool but leaves the decision right to the user, a higher tolerance for false positives was accepted.

To formalize the behaviour of false positives with the project, analysis is to be conducted on the occurrence of false positives. Usability of the tool with common libraries in the Java ecosystem will be assessed. With sufficient theoretical background to support the correctness of the algorithms, this tool is

expected to serve as an auxiliary quality control integration for open source projects that may see demand in the big data industry and other confidential data processing applications.

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