A Language-Independent Analysis Platform for Source Code

Konrad Weiss
konrad.weiss@aisec.fraunhofer.de
Fraunhofer AISEC
Garching near Munich, Bavaria, Germany

Christian Banse
christian.banse@aisec.fraunhofer.de
Fraunhofer AISEC
Garching near Munich, Bavaria, Germany

ABSTRACT
In this paper, we present the CPG analysis platform, which enables the translation of source code into a programming language-independent representation, based on a code property graph. This allows security experts and developers to capture language level semantics for security analyses or identify patterns with respect to code compliance. Through the use of fuzzy parsing, also incomplete or non-compilable code, written in different programming languages, can be analyzed. The platform comprises an analysis library and interfaces to query, interact with or visualize source code graphs. This set of CPG tools allows finding common weaknesses in heterogeneous software environments, independently of the underlying programming language.

KEYWORDS
code analysis, code property graph, software security, static analysis

1 INTRODUCTION
Ensuring the correct behavior of software is crucial to avoid security issues stemming from incorrect implementations. To ensure secure and compliant software even in the presence of ever-growing and more complex software systems, automated source code analysis tools are required. More specifically, static analysis methods are the key to consider all possible executions of a program and check whether they are running in conformance to defined expectations. Large source code bases are difficult to analyze, as methods that exhaustively simulate program states easily run into state explosion problems. Representing a finite source code base in a graph avoids such problems while still representing all program executions. Query results on such graphs are complete but not sound representations of program execution.

Research into the graph-based analysis of source code has introduced the idea of a code property graph (CPG) [5]. A CPG is a representation of source code in the form of a labeled directed multi-graph. Each node and edge is assigned a set of key-value pairs, named properties. Nodes represent syntactic elements of programming language, whereas edges capture the relations between them. These relations can be single edges, e.g. edges from call expression, source code. Our contributions are

- A language-independent graph representation and query capability of source code

2 DESIGN GOALS
With our platform, we aim to support security experts during an audit of source code and developers to perform an automated analysis e.g. in their CI/CD pipeline. These scenarios drive the following goals, that we aim to fulfill in the design and implementation of our platform:

- G1: Allow analysis of incomplete code to support its usage during the early development lifecycle and auditing where only parts of the code are available.
- G2: Create a language-independent representation to allow for definitions of rules for multiple languages and analysis of language-heterogeneous systems, such as the Cloud.
- G3: (Semi-)automated use to enable application in auditing as well as development environments.
- G4: Model language level semantics to increase precision by allowing differentiation according to nuanced language semantics.

3 GRAPH STRUCTURE
In this section, we describe the structure of our CPG, which is used to represent source code of different programming languages. This structure aims to provide a superset of language features found in most object-oriented languages, such as C++, Java or Go. This includes structural elements, such as functions, methods, classes as well as expressions/statements, e.g., calls, operators, literals or conditions.

3.1 Abstract Syntax Tree
An abstract syntax tree (AST) is a tree structure representing the syntactic elements of source code in its nodes. The root of the tree is a TranslationUnitDeclaration node, which represents the code contained in one file. The complete graph then comprises the set of all trees. Different types of AST child nodes exist in the tree, each representing different semantics within a program:

- Structural Entities represent entities that give the code its structure. Usually, they can be used as entities or instantiated as such. Examples are nodes representing namespaces, classes or structs.
- Value Declarations are identifiers that contain or return values and therefore are used to model local variables, parameters, functions, methods and constructors.

1https://github.com/Fraunhofer-AISEC/cpg
The CPG adapts the concept of a control-flow graph (CFG) into an evaluation order graph (EOG), that interconnects statements and expressions in the order that they are evaluated, to represent control flow on a finer-grained level. This is necessary to correctly capture side effects that come from the order of execution inside an expression, e.g. \(a() + b()\) or \(a > 1 \ ? \ a : b\). To build the EOG of an expression \(a + 5\), first \(a\), then \(5\) and lastly their common parent node \(a + 5\) is connected, similar to a post-order traversal of these nodes. This model of evaluation order follows the notion a compiler would follow for expression evaluation, and is extended to non-expression nodes that have an execution order. The evaluation order is from left to right with few exceptions:

- Constructs that explicitly change the control flow of a program, such as `if` or other conditional expressions.
- Nodes representing code that is not executed in the order of code appearance, e.g. the body of a for-loop being executed before its iteration expression, but after the initializer.

The root node of branching nodes is connected after the branching expression, e.g. condition or selector, and before the branching targets to allow algorithms that have traversed the branching expression to get information on the semantic root before having to handle the branch. EOG edges at such branching positions save additional information on the result of the branching expression that leads to the branch’s execution, e.g. `true` or `false` for conditions.

### 3.3 Data Flow

Operations or entities that handle data are represented in a data-flow graph (DFG) within the CPG. To model data flows through the program, the following DFG edges connect nodes:

- A child contains an edge to its parent if the parent’s value depends on the child’s value.

### 3.4 Additional program semantics

The CPG contains additional nodes and edges to model program semantics that are necessary for program analysis:

- The type system of a program and used language is modeled by adding its complex hierarchical structure as nodes and edges forming a type sub-graph, that contributes to G4.
- `REFERS_TO` edges are drawn between references and the declaration they target.
- `INVOKES` edges are drawn between calls and identified call targets in a best-effort approach to give an inter-procedural extension to the intra-procedural EOG.

## 4 ARCHITECTURE AND IMPLEMENTATION

The CPG project is composed of several tools built around a library for iterative graph construction of source code in form of a Java/Kotlin-based open source implementation. Figure 1 depicts the workflow of translating source code into the graph representation as well as its visualization and analysis by a user. The following sections will elaborate on the individual components.

### 4.1 Analysis Library

The CPG library comprises several components, which are used to configure the analysis and translation of heterogeneous code into an in-memory graph structure. Java, C and C++ are the main languages currently supported by the platform. Additionally, experimental frontends for Python, Go, TypeScript and LLVM-IR exist.

**Language Frontends.** Source code files are dispatched to a language-specific frontend by their file extension. The frontend can then either use a parsing library accessible from the JVM or use the Java Native Interface (JNI) to use language-native techniques to retrieve the AST for a particular language. A language frontend is expected to perform the following tasks:

- Language dependent AST children are translated into the language independent CPG AST structure to enable G2, as described in Section 3.1.
- Entities that are implicitly present but not located in the source code are added explicitly to the graph, e.g. implicit this fields and missing return statements.
- Identifiers are collected in a scope tree to later resolve access to names in a fuzzy manner.

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\(^2\)See https://fraunhofer-aisec.github.io/cpg/ for a complete model of the graph in our reference implementation and by node labels in the graph which contributes to G4. For example, a `MemberCallExpression`, representing a call to a class member, inherits from `CallExpression`, which in turn is derived from `Expression`.

\(^3\)We make use of JNI in our experimental frontends for Go and Python.
**Scope Manager.** In most programming languages, the declaration of a name is not globally valid, but its validity is restricted to an area associated with a language construct, such as a class or a function. This area of validity is called a scope. The scope manager tracks the currently active scope stack while the frontend traverses AST nodes. This allows for tracking and resolving declarations by absolute or relative name and managing control flow jumps that are bound to the scope of an enclosing language feature, e.g., loops, try-statements. After building the scopes in the language frontends, the scope manager holds several scope trees that allow random access in future passes.

**Passes.** As mentioned before, the frontend produces partially connected AST trees. Afterwards, passes are used to enrich the CPG by implicit execution information and program semantics such as usage-references, data-flows, and evaluation order. These semantics are built between the language independent AST nodes and are themselves language independent contributing to G2. However, they still allow for language-specific customization. Passes depend on the prior execution of other passes when needing their semantics in the graph. Lastly, passes also support inference. Nodes are added and marked as IMPLICIT, for entities that are not directly visible in source code, or INFERRRED, when part of missing source code. This allows for fuzzy parsing and analysis of incomplete code and works towards G1 by adding missing declarations of entities due to missing dependencies or code components.

The library’s functionality can be extended by any dependent applications through registration of newly implemented language frontends and passes or adapting existing components through subclassing and overwriting.

### 4.2 Persistence and Visualization

The CPG tool contains a persistence component that stores the in-memory graph into a Neo4j graph database. This allows manual exploration through interaction in a visual interface, as well as running arbitrary analysis queries written in graph-query languages.

### 4.3 CLI Console

Our platform offers a simple shell based on the interactive Kotlin interpreter $k$\textsuperscript{a} which supports semi-automated and manual analysis by auditors, as well as automatic runs of security checks for development contexts, therefore realizing our goal G3. This is achieved by providing functionality for the traversal and inspection of the in-memory graph, an extendable set of built-in commands for graph-interaction as well as a collection of security related analysis examples, such as a null-pointer detection.

### 5 EVALUATION

In this section, we assess the viability of the CPG platform in terms of runtime performance and code coverage. The evaluation is conducted over a set of 100 Java and 100 C++ open source repositories that we arbitrarily selected on GitHub. Because analysis passes are executed after all files are translated and use algorithms whose execution times are not necessarily linear to the lines of code, we compute the execution times based on the overall repositories’ SLoC and not on individual files. The collection of the repositories is not part of the measurements. The evaluation was performed on a virtual machine with a 3.3 GHz vCPU, 63 GB of Memory and 388 GB of disk space running Ubuntu 20.04.

**Execution Time (ET).** We measure the execution time (ET) in seconds / SLoC to give an impression of the expected runtime based on actual source code lines. By measuring a metric relative to the size of the repository, we aim to counter the effect that the repositories in the evaluation data set were of different sizes.

**Code Coverage.** Similar to code coverage in unit testing frameworks, we built a code coverage metric that shows how many of the original language constructs, based on the AST, were successfully represented in our final graph. The coverage is based on SLoC, with a line associated with an AST node being counted as:

- **uncovered**, if no handler was implemented for the AST node
- **covered**, if a leaf-node was properly handled or if the children of a non-leaf node were finished processing and the line is not in any of the children’s uncovered or partial set.
- **partial**, if the line is contained in one child’s uncovered set and another child’s covered set.

The algorithm to compute coverage sets in SLoC is defined recursively and shows inaccuracies in the representation. All remaining source lines, i.e., those not contained in any set so far, are added to uncovered, as these lines were not visited. Note that in contrast to AST children that cannot be handled, AST children that are not

\textsuperscript{a}https://github.com/Kotlin/kotlin-interactive-shell
forwarded to the handlers cannot be counted and their respective code is added to covered. For this reason, the results have to be considered an upper bound to the coverage.

Discussion. Table 1 shows the results of the analysis. 3 Java and 12 C++ repositories did exceed to slightly less code coverage. The execution of graph enriching passes took up less than half of the total time, 37% for Java and 46% for C++. This is not surprising as most enriched semantics are intra-procedural. The coverage metrics were previously mentioned to be imprecise and represents an upper bound to the handled source code elements. In conjunction with a lower bound metric, this upper bound would allow assessing the effectiveness of the current implementation. Upper bounds of 99% and 96% are not surprising as the implementation of analysis tools puts priority on frequently used language features.

Table 1: Runtime and coverage evaluation of 100 Repositories per Language.

| Lang. | Repos[#] | Total ET[s] | ET Passes[%] | Total SLoC[#] | ET / SLoC[ms] | FT / SLoC[ms] | Avg. SLoC[#] | Cov.[%] | Uncov.[%] | Partial[%] |
|-------|-----------|-------------|--------------|---------------|----------------|----------------|--------------|--------|-----------|-----------|
| Java  | 97        | 1042.10     | 37.5         | 211,541       | 4.92           | 2180           | 99.18       | 0.7    | 97        | 3.8       |
| C++   | 88        | 687.98      | 46.0         | 148,036       | 4.45           | 1682           | 96.19       | 3.8    | 97        | 3.8       |

6 RELATED WORK

Existing tools and techniques that build CPG analysis differ in their level of abstraction and their support for programming languages. For example, Joern [4] is a security analysis platform for several languages, such as C/C++. Java or JavaScript. Plume [1] and Graft [3] represent tools that translate Java byte-code into a graph structure. Next to CPG-related tools, CodeQL (formerly known as Semmle) [2] is a query language and engine for semantic code analysis with extensions that are specific to the supported programming languages.

Our platform differs from other tools with respect to the degree of extensibility and language abstraction. Providing an extensible platform is one of the declared goals of the CPG tool. This is achieved by providing a well-defined API to applications that allows to register new language frontends (to add support for additional languages) or passes that add additional semantics. When adding support for additional languages, developers only need to focus on translating an AST provided by a language parser into the generic CPG AST nodes (see Section 3.1). All other steps, such as call resolving, control- and data-flow construction will be executed by the existing language-independent passes. This provides reusability of implementations similar to Joern but differing both from CodeQL.

In its level of language abstraction, the CPG tool meets a balance between Joern and CodeQL. We keep more language-specific semantics by modeling a more differentiated set of AST nodes and type hierarchy than Joern, while keeping resulting queries language independent. CodeQL in contrast, uses a loose system of generic AST type-interfaces and highly language-specific implementations that do not allow for language-independent queries.

7 CONCLUSION

In this paper, we present the CPG tool, a platform of tools to analyze source code written in different programming languages using a uniform graph representation. We show, using an evaluation of 200 source code repositories, that the CPG is suitable to analyze small to medium-size repositories, independently of the programming language. It offers coverage of the most common language constructs, especially for the C/C++ and Java languages. The evaluation of our translation execution times, shows that suitable scenarios include security audits or checks during CI/CD runs. However, further improvements are necessary to allow real-time code analysis in the early development cycle. Future work, therefore, includes the parallelization of code translation as well as the incremental construction of graphs and program semantics.

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