Wasmati: An Efficient Static Vulnerability Scanner for WebAssembly

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ABSTRACT

WebAssembly is a new binary instruction format that allows targeted compiled code written in high-level languages to be executed with near-native speed by the browser’s JavaScript engine. However, given that WebAssembly binaries can be compiled from unsafe languages like C/C++, classical code vulnerabilities such as buffer overflows or format strings can be transferred over from the original programs down to the cross-compiled binaries. As a result, this possibility of incorporating vulnerabilities in WebAssembly modules has widened the attack surface of modern web applications.

This paper presents Wasmati, a static analysis tool for finding security vulnerabilities in WebAssembly binaries. It is based on the generation of a code property graph (CPG), a program representation previously adopted for detecting vulnerabilities in various languages but hitherto unapplied to WebAssembly. We formalize the definition of CPG for WebAssembly, introduce techniques to generate CPG for complex WebAssembly, and present four different query specification languages for finding vulnerabilities by traversing a program’s CPG. We implemented ten queries capturing different vulnerability types and extensively tested Wasmati on four heterogeneous datasets. We show that Wasmati can scale the generation of CPGs for large real-world applications and can efficiently find vulnerabilities for all our query types. We have also tested our tool on WebAssembly binaries collected in the wild and identified several potential vulnerabilities, some of which we have manually confirmed to exist unless the enclosing application properly sanitizes the interaction with such affected binaries.

KEYWORDS

WebAssembly, Vulnerability, Static Analysis, CPG, Security

1 INTRODUCTION

WebAssembly [16] is an emerging binary code format designed for speeding up the Web. Currently supported by all major browsers, WebAssembly bytecode runs on a stack-based virtual machine that takes advantage of the local hardware capabilities to achieve near-native execution performance. Also known as Wasm, WebAssembly is a low-level assembly-like language as well as a compilation target for higher-level programming languages like C++. This feature has prompted swathes of pre-existing C++ libraries and applications to be ported to run in the browser [7], boosting the adoption of Wasm in the Web [26]. WebAssembly’s portability and efficiency have led to its usage far beyond the browser, being employed for running sandboxed code of server-side web applications [9, 13, 38], IoT apps [17], edge computing logic [29], or smart contracts [28].

However, WebAssembly opens up new avenues for the introduction of security vulnerabilities in the Web and other Wasm-based environments [22]. Albeit the extensive safety mechanisms incorporated into WebAssembly itself, many coding errors and unsafe functions written in C or C++ can still be transposed into WebAssembly binaries. As a result, web application code that depends on WebAssembly modules may now become crippled by the introduction of classic forms of software security flaws, such as format strings, use-after-free, double free, or buffer overflow vulnerabilities. Preliminary studies have shown that when such flaws are present in Web applications, they may be leveraged for launching several web attacks, such as cross-site scripting (XSS) or code injections [24].

Given the pace at which many software projects are being ported to WebAssembly and being adopted worldwide [18], we foresee the imminent danger of pre-existing vulnerabilities to creep into many applications and potentially cause much damage in the near future. As a preemptive measure to tackle this risk, our focus in this work is to help eliminate potential security flaws in WebAssembly binaries, regardless of the specific target application where these binaries are used, e.g., as part of a client-side web page running alongside JavaScript code, as a server-side module running on a Node.js application, or even as a component of a browser extension.

To root out many security flaws from Wasm modules, one can compile these modules from code written in safe programming languages like Go or Rust. However, porting countless software written in C/C++ to a safe language would be a daunting and impractical endeavor. Alternatively, checking and fixing vulnerabilities in C/C++ code using vulnerability scanner tools would proactively counter the transposition of security bugs to Wasm binaries. However, WebAssembly applications are normally composed of multiple libraries or modules, most of which have been precompiled independently by third parties. Access to the original sources may not even be possible (e.g., proprietary code). We then propose a third alternative based on the direct analysis of WebAssembly binaries.

This paper presents Wasmati, an efficient static analysis tool for finding vulnerabilities in Wasm binaries. Wasmati can be shipped in the form of a library that can be linked to other programs (e.g., infrastructure-level software or security analysis frameworks) or packaged as a standalone CLI program. It can then be used for checking vulnerabilities at the development stage (e.g., in the software
development toolchain) or in the production stage (e.g., for analyzing client-side web applications in the wild). Currently, our tool can analyze Wasm binaries generated by the popular Emscripten [12] compiler. Wasmati is parameterized by a collection of vulnerability queries. By enriching this set of queries, one can augment the typology of vulnerabilities that Wasmati can detect.

To build Wasmati, we adopt a recently proposed static program analysis technique named code property graph (CPG) [42, 43]. CPGs have proved to be powerful constructs for building vulnerability scanners at the source code level for languages such as C/C++ [1, 2, 5], Java [1, 5], Python [1, 5], or PHP [8], and also at the low virtual machine code level for LLVM [5] and Java bytecode [6]. Wasmati is the first tool of this kind to analyze WebAssembly bytecode.

In the design of Wasmati, the low-level nature and specific semantics of WebAssembly brought about several non-trivial challenges. In the construction of the CPG, a major obstacle was in devising a scalable technique to analyze complex Wasm binaries. In Wasm code, the number of nodes of a CPG grows dramatically. Adding to the fact that CPG requires multiple graph traversals for adding edges relative to its distinct subgraphs, the overall construction of a CPG can become prohibitively slow even for modest-sized libraries. For query specification, a core challenge is to represent CPG search patterns while satisfying three requirements: i) expressiveness power, i.e., allow the detection of vulnerability types through the traversal and inspection of the CPG’s properties, ii) conciseness and simplicity, i.e., allows security analysts to easily specify new queries, and iii) performance, i.e., the evaluation of queries must terminate in an acceptable time, viz. in a few seconds or minutes.

Wasmati features an optimized CPG data structure and generator engine that significantly speeds up the CPG generation process. Some of the optimization strategies include i) enriching the GPG graph with additional annotations, ii) caching intermediate results, and iii) employing efficient graph traversal algorithms. As for query specification, to strike a good balance between expressiveness power, conciseness, and performance, we developed a domain-specific language named Wasmati Query Language (WQL). WQL allows security analysts to specify vulnerability patterns in a developer-friendly way while offering efficient query execution times. To study how WQL performs in comparison with alternative query specification languages, Wasmati features a generic CPG query engine that enables queries to be specified and executed in three additional languages: C++, Datalog, and Neon’s Cypher.

We implemented 10 different vulnerability queries and extensively evaluated Wasmati using four different Wasm binary datasets. Wasmati found 100 vulnerabilities out of 108 present in these datasets, representing a precision of 92.6%. This shows that vulnerabilities in WebAssembly can be modeled using CPGs. Wasmati’s generation of CPGs can scale for large real-world applications. Using SPEC CPU 2017, the construction time averaged 58 seconds per binary. Graph construction is polynomial in time given the graph’s size. We executed the 10 queries in generated CPGs of SPEC CPU 2017 with an average execution time of 77 seconds. We tested Wasmati on a dataset comprising real-world WebAssembly binaries and found several potential vulnerabilities. We manually analyzed some of the flagged vulnerabilities and confirmed that they can be triggered by crafted inputs provided into the affected module.

In summary, this paper makes the following contributions: (1) first formalization of CPGs for WebAssembly, (2) techniques for efficient generation of WebAssembly CPG and specification of vulnerability queries for Wasm code, (3) robust implementation of the Wasmati tool, (4) extensive evaluation using real-world Wasm binaries and queries written in four different languages.

2 BACKGROUND AND OVERVIEW

In this section, we introduce WebAssembly, motivate our work using a real-world vulnerability that persists in WebAssembly, provide an overview of how Wasmati detects this vulnerability and, finally, clarify the design goals and scope of our new tool.

2.1 Background on WebAssembly

The WebAssembly binary is a sequence of instructions that are executed on a stack-based machine. Simple instructions perform operations on data; they consume their operands from the stack and produce a result that is placed on the stack. Control instructions alter the control flow of the code. A program can call functions directly or indirectly through a function table. Figure 1 a) shows a direct call of the index 2. Indirect calls allow the emulation of function pointers and polymorphism in OOP languages such as C++. The table index value is pushed into the stack, evaluated at execution time, and the function indexed by that value is executed. Function tables can be defined in modules. A module represents the binary format of Wasm that has been compiled.

WebAssembly has only four primitive types: 132, 164, f32 and f64. The first two represent integers with 32 and 64 bits respectively, whereas the last two denote 32 and 64-bit floating-point data. Global variables, local variables, and return addresses are managed in the stack. All non-scalar types, such as strings, arrays, and other buffers, must be stored in linear memory, which is a contiguous, untyped, byte-addressable array, multiple of 64Kib. A program can load/store values from/to linear memory at any byte address. A trap occurs if an access is not within the bounds of the current memory size.

WebAssembly binaries are executed by a runtime engine. They are normally deployed in the form of modules that pertain to a larger JavaScript application (see Figure 1 b)). Applications use dedicated JavaScript code to bootstrap the Wasm module into a sandboxed environment and to interface with external resources (e.g. DOM). JavaScript code and WebAssembly modules can mutually expose function calls and communicate with each other through shared linear memory. WebAssembly-based applications can run on various platforms, most commonly on the browser, but also on web servers (e.g., powered by Node.js) or desktops.
void get_token(FILE *pnm_file, char *token) {
    int i = 0;
    int ret;
    // (....)
    do {
        ret = fgetc(pnm_file);
        if (ret == EOF) break;
        i++;
        token[i] = (unsigned char) ret;
    } while ((token[i] != '\n') && (token[i] != '\r')
    && (token[i] != ' '));
    token[i] = '\0';
    return;
}

Figure 2: Buffer overflow in libpng (CVE-2018-14550).

void main() {
    std::string img_tag = "<img src='data:image/png;base64,";
    // bad input: AAAA...AA<script>alert('XSS!')</script>!-
    pnm2png("input.pnm", "output.png"); // CVE-2018-14550
    img_tag += file_to_base64("output.png") + ";">
    emcc::global("document").call("write", img_tag);
}

Figure 3: Exploit for CVE-2018-14550 by Lehman et al. [22].

2.2 Practical Vulnerability Example

Figure 2 presents an example of a real stack buffer overflow vulnerability (CVE-2018-14550 [10]) existing inside libpng, which is the official PNG reference library and it is widely used by many applications. Affecting the function get_token, this vulnerability can persist when this code is compiled from C to WebAssembly and it has been previously used by Lehman et al. [22] to showcase how vulnerable code written in memory-unsafe languages can be transferred to WebAssembly modules. By developing the exploit presented in Figure 3, the same authors have shown that this flaw can be harnessed to launch a cross-site scripting (XSS) attack. We leverage the same example to motivate our work and then, in the next section, we illustrate how our tool can detect this vulnerability.

The buffer overflow vulnerability shown in Figure 2 can be triggered when converting a PNM file to a PNG file using libpng. This operation calls get_token by providing a 16-byte length local buffer as the token parameter. Inside get_token no check is performed to assess if this buffer is being written beyond its 16-byte length, which allows for a stack buffer overflow to occur whenever the pnm_file parameter exceeds 16 bytes. Normally, when libpng is compiled to native binary code, stack canaries prevent this vulnerability from being exploited. Even if stack canaries are not employed by the compiler, the buffer overflow is limited to the stack. However, in WebAssembly this vulnerability can be freely exploited without any of these mitigation strategies. Additionally, when taking into account different linear memory layouts from WebAssembly compilers and backends, this vulnerability can lead to writes not only in the stack, but also the heap and data sections of the memory.

The C++ code in Figure 3 represents a simplified version of a service that converts images using the libpng library and then displays the converted image by writing the content to the DOM using the document.write function. This code converts a PNM image to PNG (line 4), encodes the image content in base64, appends the image content into the img tag (line 5), and then adds the tag into the document by manipulating the DOM (line 6). Since the image content is embedded into the DOM as a base64-encoded string, it normally cannot lead to XSS. However, the stack-based buffer overflow in libpng allows the attacker to overwrite higher addresses, including the heap, which holds the C++ string with the img tag (line 2). This way, the attacker can use a crafted malicious input, such as the script tag string containing an alert (line 3) as the content of the image to convert and override the img tag with the new crafted script tag, thus causing an XSS attack.

2.3 Finding Vulnerabilities With Wasmati

To cater for the static detection of C/C++-style vulnerabilities in Wasm code, we generate and analyze WebAssembly-specific Code Property Graphs (CPGs). GPGs are graph-based data structures that allow for a stack buffer overflow to occur whenever the...
which include information about the analyzed code in the form of property-value pairs (hence the name CPG). These pairs can then be queried in different ways to search for different types of vulnerabilities that can exist in the analyzed code. Using our CPG specification for WebAssembly, Wasmati can detect the buffer overflow vulnerability in the libpng presented in Figure 2 by analyzing the corresponding WebAssembly code representation listed in Figure 4.

Next, we give an overview of Wasmati CPGs and then explain how this vulnerability can be detected by searching for a specific pattern in the CPG’s sub-graphs of the corresponding WebAssembly code.

1. Generating the CPG: Figure 5 depicts part of the CPG generated by Wasmati for the code shown in Figure 4. The WebAssembly CPG is comprised of four different graphs: Abstract Syntax Tree (AST), Control Flow Graph (CFG), Data Dependency Graph (DDG), and Call Graph (CG). The first three are portrayed in Figure 5 being distinguished by the edge colors. For clarity, AST edges are illustrated by green edges and node properties are not represented in the figure. A full description of node properties can be found in the appendix. The CPG explicitly describes the order by which instructions are executed and the conditions necessary for taking a particular execution path. The CFG edge, illustrated in red, may contain a label that helps identify the condition that allows that particular flow to be followed. The DDG explicitly represents dependencies between the instructions of the program. Dependencies can be function calls, local variables, global variables or constants. Each dependency is expressed as an edge painted in blue and its label refers to the name of the dependency. The CG is essential to support inter-procedural analysis and is a simple directed graph that connects call nodes and the root of the corresponding called function. It is not visible in Figure 5 as we are not analyzing an inter-procedural case, but we explain its importance in Section 4.

To better visualize the CPG, the nodes in this figure are arranged in a tree layout (corresponding to the AST) with five sub-trees which are numbered from 1 to 5. Each sub-tree can be seen as a bigger tree layout (corresponding to the AST) with five sub-trees which are numbered from 1 to 5. Each sub-tree can be seen as a bigger

2. Querying the CPG: The idea to find this type of vulnerability i.e., buffer overflows in WebAssembly code is to analyze the CPG searching for characteristic patterns. In WebAssembly, buffer overflows happen when a buffer is incorrectly used inside a loop, e.g., when handling strings. A vulnerability may occur because the index of the buffer is incremented and the buffer’s bounds are not being checked as part of the loop’s exit condition. The idea to detect buffer overflows then is to search for instructions in a loop where the AST descendants (loop’s block and condition): 1) contain a local variable $i$ representing the index that is being incremented, 2) have a store instruction that depends on a buffer and $i$ (assignment), and 3) lack an exit br if whose condition test verifies the boundaries of $i$. Thus, to find the vulnerability in our running example, we can query the CPG looking for patterns that satisfy these three conditions. For the first, we look for instructions i32.add that have incoming local DDG edge for $i$ and a constant DDG edge (which is the increment value). For the second, we simply look for store instruction with incoming local DDG edge for $i$. And lastly, we search for br if instructions and query its AST descendants (representing the composite condition) for the existence of comparison instruction with incoming local DDG edge for $i$. This idea can then be generalized to look for other types of vulnerabilities by adjusting the CPG query accordingly.

2.4 Design Goals and Scope

Our main goal is then to build a static analysis tool that can detect security flaws that can be propagated from the original programs (typically written in a high-level language like C/C++) into WebAssembly binaries. We are also interested in building efficient query engines that can help us study several inherent trade-offs between query expressiveness, power, conciseness, and performance.

The analysis implemented by our tool will be focused on individual Wasm modules independently of how they are used by a given application or the platform where they are deployed. To examine how a particular security flaw in a Wasm module would manifest itself in a full-blown application, it would be necessary to analyze not only individual WebAssembly binaries but also all other application components (including JavaScript code), which fall outside the scope of this paper due to a significant added complexity.

3 WASMATI ARCHITECTURE

We present Wasmati, a new static analysis tool based on the generation of CPGs for finding security vulnerabilities in WebAssembly binaries. We implemented Wasmati using C++11 in about 12,350 lines of code. Figure 6 represents the internal components of our
Wasmtool. Wasmtool consists of two processing pipelines: the CPG generator pipeline and the query engine pipeline. The former is responsible for analyzing an input Wasm program and generating the corresponding CPG data structure into a file. The query engine pipeline loads the CPG from this file and executes a series of queries by searching for specific vulnerability patterns in the CPG. Below, we briefly describe the inner workings of each processing pipeline.

CPG generator pipeline: Wasmtool receives a Wasm module, in binary or text format, which will be fed into WebAssembly Binary Toolkit (WABT) [15]. We used WABT, an open-source project maintained by the official WebAssembly community, to parse the WebAssembly’s binary/text formats. The parser produces a list of functions. This list is processed by a chain of components which progressively build the CPG. First, this list is provided as input to the abstract syntax tree (AST) builder which creates the AST. Then, the control flow graph (CFG) builder generates the CFG by making another iteration over the function list; the call graph (CG) is also generated in this stage. Lastly, the data dependency graph (DDG) builder creates the DDG. The resulting CPG is then written to a file in one of several possible serialization formats.

Query engine pipeline: The query pipeline supports four query languages/back-ends to execute the CPG traversals:

1. **WQL**: is the Wasmtool Query Language, a DSL that eases the writing of CPG traversals for WebAssembly. The queries written in WQL are interpreted by the WQL interpreter. WQL strikes a good balance between expressiveness power, specification simplicity, and performance. The following back-ends explore different trade-offs in the design space which we explain more thoroughly in Section 5.
2. **Native**: consists of a query API that enables Wasmtool to be extended with additional queries written in C++. Adding new queries requires the re-compilation of Wasmtool.
3. **Neo4j**: is a graph database that can import the serialized CPG and be traversed using Cypher Query Language (CQL). Wasmtool comes with a Dockerfile and scripts to import and run queries automatically. A new query can be added to a specific folder.
4. **Datalog**: is a declarative logic programming language that allows the Wasm CPG to be queried in a deductive manner. Wasmtool uses Soufflé’s [20] flavoured datalog and its engine. Alongside a Docker configuration file, which automatically imports and executes data-log queries, Wasmtool also comes with a library containing common predicates and definitions to query the CPG.

Currently implemented queries: We focused on five main classes of common vulnerabilities in C/C++ that can still persist in the compiled Wasm code: format strings, dangerous functions, use-after-free/double-free and different variations of tainted-style vulnerabilities and buffer overflows. To detect these types of vulnerabilities, we implemented a total of ten different queries in each of Wasmtool’s supported query languages. Regarding tainted-style vulnerabilities, we implemented three variants: tainted call indirect, tainted function-to-function, and tainted local-to-function. In the first, we query the taintability of the last argument of call indirect which controls the function to be called. The second looks for the classical result of an input source reaching a sink. The third looks for a possible tainted parameter that reaches a sink. With respect to buffer overflows, we also target three variants: static buffer overflow, where we compare the size of the buffer against the size of the data being written to it; malloc buffer overflow, similar to static buffer overflow but the buffer is allocated dynamically with a constant value; and loop buffer overflow, where we search for buffer writes without boundary checks – this variant can detect a buffer overflow in libpng (CVE-2018-14550) [10].

In the following sections, we describe in detail the core challenges and operations performed by the processing pipelines of Wasmtool, namely building and querying WebAssembly CPGs.

## 4 BUILDING WEBASSEMBLY CPGS

The specific features of WebAssembly introduce non-trivial obstacles to the construction of WebAssembly CPGs which required us to: (i) formalize a tailor-made data structure for representing WebAssembly CPGs, (ii) develop a specific data flow analysis algorithm for computing WebAssembly DDGs, and (iii) incorporate a set of optimizations to speed up the process of building CPGs. In this section, we present how Wasmtool builds WebAssembly CPGs emphasizing these main distinguishing features of our system.

### 4.1 Specification of WebAssembly CPGs

Formally, a CPG $G = (V, E, \mu)$ is a triple such that: (i) $V$ is the set of nodes, (ii) $E$ is the set of edges connecting the nodes in $V$, and (iii) $\mu : V \cup E \rightarrow K \rightarrow \mathcal{V}$ is a total function linking each vertex/edge to a (partial) map connecting its properties to their values. For instance, let $n$ be a node in $V$, the function $\mu(n) : K \rightarrow \mathcal{V}$ maps the properties of $n$ to their corresponding values. For clarity, we use $\mu(n, k)$ instead of $\mu(n)(k)$ to denote the value of property $k$ of node $n$. Not all nodes/edges define all the properties in $K$. More concretely, each type of node/edge defines its own specific properties; for instance, store/load instruction nodes define a property `offset` for holding the offset associated with their respective instructions.

A CPG $G = (V, E, \mu)$ can be decomposed into four sub-graphs, respectively corresponding to the AST, CFG, CG, and DDG of the program to be analyzed. For instance, we write $G_{AST} = (V, E_{AST, \mu_{AST}})$ for the AST component of $G$. While these four graphs share the same underlying set of nodes, $V$, they have different edges and they store different property-value pairs. Importantly, each edge $e \in E$ is...
associated with a property type, indicating the sub-graph to which it belongs (i.e. \( \mu(e, \text{type}) = \text{AST means that } e \in E_{\text{AST}} \)).

**Abstract Syntax Tree (AST):** To build the AST, we leverage the official open-source parser included in WABT\(^1\). However, the AST produced by the WABT parser is a flat tree, and for the purpose of CFG query traversal this lack of structure makes it hard to analyze instructions that take multiple input arguments (e.g., \( i32 \cdot \text{add} \), or function calls). To overcome this limitation, we re-arrange the array of instructions produced by the parser to make sure that direct dependencies are taken into account resulting in a hierarchical organization. For instance, in the program of Figure 5, the instructions local.get \$i and \( i32 \cdot \text{const} \) become children of \( i32 \cdot \text{add} \) (sub-tree 2), while the original parser represents the three instructions at the same level. To perform this re-organization, Wasmapi implements an “AST folding” algorithm (shown in the appendix).

Our AST includes additional nodes that store meta-information concerning the WebAssembly program; for instance, we use the node return to pinpoint the expression that computes the return value of a function.

**Control Flow Graph (CFG):** In our case, building the CFG is relatively simple because the WebAssembly control flow is structured and can be statically verified. In contrast to typical native binaries (e.g., for x86 or Arm), in WebAssembly there are no relative jumps and a jump target cannot be an instruction from the middle of a block. Wrong paths are not allowed and are validated before execution by the runtime. As a result, the WebAssembly CFG is mostly linear: each instruction has a CFG edge connecting it to the next instruction in the code. The exceptions are the branching instructions if, br_if and br_table, which have more than one successor node. Unsurprisingly, the two outgoing edges of if and br_if are labeled with either true or false to distinguish the then branch from the else branch. Analogously, the instruction br_table, which works as a switch statement in a high-level language, has its outgoing branches annotated with the concrete values that cause the control to be transferred to each of its branches. Finally, branching labels are stored in the property label of the corresponding CFG edge. For instance, given a CFG edge \( e \in E_{\text{CFG}}, \mu(e, \text{label}) = \text{true} \) means that \( e \) is the then branch of a br_if instruction.

**Call Graph (CG):** Call graphs are essential to support inter-procedural analysis. In a nutshell, a call graph is a simple directed graph that connects call nodes (i.e., nodes representing call instructions) to the root nodes of the corresponding functions. To implement a CG in WebAssembly, we have to consider both direct calls and indirect calls. Direct calls are processed straightforwardly: each direct call instruction is directly connected to the node representing the function being called. However, indirect calls are more difficult to analyze, as the index of the function being called is computed at runtime. An indirect call is a mechanism that allows polymorphism from OOP source languages (e.g. C++) and is dependent on its execution. As a result, it is impossible to determine statically which functions will be executed. In fact, multiple functions can be executed depending on different executions.

We solve this challenge as follows. In WebAssembly, for a dynamic call to be executed successfully: 1) the called function must be stored in the function table, and 2) the signature of the called function must coincide with the signature supplied to the call instruction. Hence, for indirect calls, we simply connect every indirect function call to all the function nodes whose signatures match the statically supplied signature. Finally, all CG edges have a single property type with value CG, tagging them as part of the call graph.

**Data Dependency Graph (DDG):** A DDG explicitly represents dependencies between the instructions of the program to be analyzed. In the original CPG paper [42], it is comprised of both data dependencies and control dependencies, which the authors coalesce into a Program Dependency Graph (PDG). An instruction \( \text{inst}_2 \) data-depends on another instruction \( \text{inst}_1 \), if \( \text{inst}_2 \) uses a variable defined by \( \text{inst}_1 \). In turn, \( \text{inst}_2 \) control-depends on \( \text{inst}_1 \), if the execution of \( \text{inst}_2 \) depends on \( \text{inst}_1 \) (e.g., \( \text{inst}_1 \) is a branch instruction).

However, the original PGD definition for CPGs is not ideal for WebAssembly. For one, keeping track of both dependency types leads to inefficiencies and scalability bottlenecks when constructing and when querying the graph. Compiled WebAssembly code contains many instructions organized in long chains of conditional blocks and loops which may result in an exceedingly large number of control dependencies edges (in our preliminary experiments, comprising in some cases 98% of the total edges of a program’s CPG and bloating its size up to 65 times). Secondly, the original PDG definition [42] is too coarse. In WebAssembly, we require richer semantics that allows us to reason about different variable scopes (local and global), return values from function calls, and constant value propagation. For instance, we need to differentiate variables from constants given that oftentimes the compilation of an instruction in C that uses a constant value translates into multiple WebAssembly instructions accessing local variables, making it difficult to keep track of the constant in the WebAssembly binary.

Hence, for building WebAssembly data dependencies we employ two specific adaptations: i) we discard the calculation of control dependencies as it is easily queried later through the CFG, and ii) use a custom-made dependency analysis that combines reaching definitions and constant/function propagation. This leads to our

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\(^1\)https://github.com/WebAssembly/wabt
definition of Data Dependency Graph (DDG). More concretely, we track four types of data-dependencies: (1) a constant dependency \( C_{id}(v, t) \) represents a data-dependency on a constant value \( v \) of type \( t \), generated by the instruction with identifier \( id \); (2) a function dependency \( F_{id}(f) \) represents a data-dependency on the value returned by function \( f \), called at instruction with identifier \( id \); (3) a global dependency \( GV_{id}(x) \) represents a data-dependency on the value of a global variable \( x \) (through the instruction with identifier \( id \)); and (4) a local dependency \( LV_{id}(x) \) represents a data-dependency on the value of a local variable \( x \). In the following, we use \( \phi \) to range over the set of dependences \( \phi \in \Phi \) and \( \psi \) to denote an arbitrary set of dependencies \( \psi \subseteq \Phi \). Put formally:

\[
\phi \in \Phi \; \overset{\text{def}}{=} \quad C_{id}(v, t) \lor F_{id}(f) \lor GV_{id}(x) \lor LV_{id}(x)
\]

where: \( v \) ranges over the set of WebAssembly values, \( t \) over the set of WebAssembly types, \( f \) over the set of function identifiers, and \( x \) over the set of global and local variable names.

To better understand how dependencies are modeled, let us consider the WebAssembly program and DDG given in Figure 7. Each node’s identifier is displayed in its upper-left corner. In particular, one can see that instruction 6 depends on the value of the local variable \( y \), which is put on top of the stack by instruction 4. This dependency is modelled as: \( LV_y \). One can further see that instruction 6 also depends on the constant value 2 put on top of the stack by instruction 5. This dependency is modelled as: \( C_{i2} \).

Dependencies are computed by a data-flow analysis explained next. Having computed the dependencies of every instruction, the construction of the DDG is straightforward. Each node is simply connected to the nodes on which it depends and DDG edges are labelled with attributes of their corresponding dependencies. For instance, let \( e_1 \) be the edge connecting nodes 4 and 6 in the DDG given in Figure 7. We have that: \( \mu(e_1, \text{type}) = \text{DDG}, \mu(e_1, \text{ddgType}) = \text{Local}, \) and \( \mu(e_1, \text{name}) = y \). A complete description of the property-value pairs of DDGs is given in the appendix.

### 4.2 Dataflow Analysis for WebAssembly

The construction of the DDG is the most challenging of all the CPG’s sub-graphs as it requires a data flow analysis that takes into account the specific features of WebAssembly. In this section, we formally explain the steps and calculations implemented to track the data dependencies necessary for the DDG use case. As discussed above, despite applying known dataflow analysis, these data dependencies had to be adapted to our model and WebAssembly itself.

We apply the monotone framework to compute WebAssembly dependencies by lifting concrete states to abstract states. While a concrete state is composed of a concrete linear memory, global store, local store, and stack. Our abstract states do not have the linear memory component as we do not track dependencies that are established through the use of linear memory operations. Instead, abstract states are simply composed of an abstract global store, local store, and stack. In a nutshell, an abstract global store \( \hat{g}: G^V \rightarrow \phi(\Phi) \) is a mapping from global variables to sets of dependencies \( \phi(\Phi) \). Analogously, an abstract stack, \( \hat{s} \), is simply a list of sets of abstract dependencies.

For instance, \( \hat{g}(s\emptyset) = C_{i2}(3, i32) \) means that \( s\emptyset \) depends on the constant value 3 via the instruction with identifier 20.

To calculate the data dependencies at each execution point, we traverse the CFG of the program to be analyzed, propagating dependencies in a forward manner. More concretely, we define, for each instruction, a transfer function that describes how that instruction propagates data dependencies by specifying how the output data dependencies are computed using the input data dependencies. Put formally, we define a general transfer function \( T : I \times S \rightarrow \hat{S} \) that computes an output abstract state given an instruction in \( I \) and an input abstract state. The function \( T \) is defined as a set of rules that follow the syntax of instructions. Below, we show a few selected rules, while the complete set of rules is given in the appendix.

Transfer functions (fragment):

\[
T(x) = \begin{cases} 
C_{i2}(f, s) & \text{if } x = C_{i2}(f, s) \\
F_{i1}(f) & \text{if } x = F_{i1}(f) \\
\mathcal{G}(x) & \text{if } x = \mathcal{G}(x) \\
\mathcal{L}(x) & \text{if } x = \mathcal{L}(x) \\
\mathcal{S}(x) & \text{if } x = \mathcal{S}(x) \\
\end{cases}
\]

Given the transfer functions, we compute the dependencies of each instruction by traversing the CFG of the program starting from the entry point of each function. Loop instructions are re-visited if their input dependencies change. The complete algorithm and the full list of transfer functions are given in the appendix.

### 4.3 Algorithmic Complexity

We analyze the complexity of our algorithm for constructing WebAssembly CPGs by focusing on each sub-graph at a time.

The construction of the AST graph is done in linear time in the number of instructions of the original program. The complexity of the construction algorithm is dominated by the cost of the AST folding algorithm given in the appendix (Algorithm 1). Using aggregate analysis, we conclude that the total number of iterations of both the outermost and the innermost loops is linear in the number of instructions. In particular, we note that each node has at most one parent in the AST graph, meaning that it can only be visited once by the innermost loop.

The construction of both the CFG and the CG graphs is done in linear time in the number of instructions of the original program. The construction algorithms simply traverse the instruction nodes of the program; the CFG algorithm connects each node to its immediate successors, while the CG algorithm connects direct and indirect call nodes to their corresponding functions. In both cases, the processing of each instruction is done in constant time, making both algorithms linear in the number of traversed instructions.

The construction of the DDG is done in quadratic time in the number of instructions of the original program. The cost of this algorithm is dominated by the dataflow analysis described in Section 4.2. To determine the cost of the dataflow analysis, we have to determine an upper-bound on height of the state lattice, which bounds the number of iterations that the dataflow analysis can perform [27]. Recalling that each state is composed of an abstract global
store $\hat{\xi} : G\mathcal{V} \rightarrow \xi(\Phi)$, an abstract local store $\hat{t} : \mathcal{L}\mathcal{V} \rightarrow \xi(\Phi)$, and an abstract stack $\hat{s}$, we note that the height of the state lattice corresponds to the joint size of the domains of the three state components $(|G\mathcal{V}| + |L\mathcal{V}| + |\mathcal{S}\mathcal{T}|)$ times the height of the dependency lattice ($\xi(\Phi)$); put formally:

$$H = (|G\mathcal{V}| + |L\mathcal{V}| + |\mathcal{S}\mathcal{T}|) \times |\Phi|$$  \hfill (2)

where $|\mathcal{S}\mathcal{T}|$ denotes an upper bound on the size of the stack. Observing that both $|G\mathcal{V}| + |L\mathcal{V}| + |\mathcal{S}\mathcal{T}|$ and $|\Phi|$ are bounded by the total number of instructions, we conclude that the construction of the DDG is done in quadratic time.

### 4.4 Optimizations

The distinct structures that make up a CPG amount to a high number of nodes and edges. This is especially true for WebAssembly, which is a low-level language with many instructions which tends to require the generation and analysis of a very large graph even for relatively small binaries. The high number of nodes and edges hampers the scalability of our system with respect to memory usage and computing time for both CPG generation and graph traversals (queries). For example, regarding CPG generation, the biggest bottleneck is the construction of the DDG, mainly in the analysis of loops, because it has to traverse the graph multiple times and calculate data dependencies until no changes are made to the set of dependencies. This is very expensive as we realized that typical WebAssembly programs contain multiple chained loops.

To improve the efficiency and scalability of Wasmati, we employed several optimizations to construct the CPG in useful time without overwhelming the memory usage. The most relevant were as follows: 1) We pre-compute, for each type signature in the program, the set of functions with that signature that can be called indirectly, thus simplifying the generation of the call graph; 2) We propagate dependencies in a modular fashion, meaning that we only compute the dependencies of the successor of a loop, after computing the dependencies of the loop itself; this requires us to keep track of loop exits during data-flow analysis; 3) We cache the dependencies of inner loops to avoid re-analyzing them during new iterations of the outer loops; 4) We avoid the implementation of recursion as it had a negative impact due to indirectness and high number call stack frames (eventually running out of stack memory). Every traversal/calculation was made in an iterative version.

### 5 QUERYING WEBASSEMBLY CPGS

Vulnerabilities often give rise to specific CPG patterns that can be found using graph queries. Hence, the detection of a security flaw in WebAssembly can be achieved by specifying a graph query that captures the corresponding pattern. Wasmati comes with four query engine pipelines that can process queries in specified different languages. Next, we present WQL: Wasmati’s dedicated query language for specifying and executing CPG queries. Then we give a brief account of the remaining query back-ends, explaining the rationale for their development and describing how they work.

#### 5.1 Wasmati Query Language (WQL)

We introduce WQL by example, explaining how it can be used to encode and detect typical C/C++-style security vulnerabilities, namely **use-after-free vulnerabilities**, **taint-style vulnerabilities**, and **buffer overflows**. Other common security vulnerabilities, such as use of **dangerous functions, format strings**, and **double free** can also be easily expressed using WQL. The complete list of queries used to assess Wasmati is given in the appendix.

**WQL features**: WQL is a simple interpreted imperative language that offers a wide range of built-in functions for traversing and inspecting the underlying CPG. WQL supports the standard primitive types: booleans, floats, integers, and strings. It also supports polymorphic lists and maps, as well as CPG nodes and edges. When it comes to control flow, WQL includes the typical control flow constructs: if-then-else, while, foreach, break, and continue. Furthermore, WQL has a dedicated syntax for range-expression, which is often useful for concisely implementing queries. We write $[\ n \ in \ \mathcal{S}\mathcal{T} \ : \ pred \ ]$ to denote the list obtained by removing from $\mathcal{S}\mathcal{T}$ all its elements that do not satisfy $pred$.

**Use-after-free vulnerabilities** occur when one uses a reference to a memory location that has already been freed. This may lead to undefined system behavior and, in many cases, to a write-where-condition. It can compromise the integrity and/or availability of the system by causing it to crash or lead to the corruption of valid data when that memory area has already been re-allocated.

Figure 8 shows the WQL query for detecting use-after-frees. Our goal is to find three nodes $n_1$, $n_2$, and $n_3$ such that: (1) $n_1$ holds a call to malloc; (2) $n_2$ holds a call to free, which frees the memory segment allocated at $n_1$; and (3) $n_3$ holds any instruction that executes after $n_2$ and uses the pointer returned by the instruction at $n_1$. In order to find such three nodes, we iterate over each function in the CPG. For each function, we first obtain all possible candidates for $n_1$ (line 2). For each possible $n_1$, we then obtain all possible candidates for $n_2$ (line 4). In order to do this, we make use of the predicate $\text{reachesDDG}(n_1, n, \text{“Function”, “$\text{malloc}$”})$ to identify only the nodes that depend on $n_1$ via the value returned by $\text{malloc}$. Finally, we use the built-in function $\text{descendantsCFG}$ to obtain all the descendants of $n_2$ and then filter these descendants to obtain only those that depend on $n_1$ (line 6); if the resulting list is not empty, a **use-after-free vulnerability** is flagged.

**Taint-style vulnerabilities** refer to data flows from attacker-controlled sources to security-sensitive sinks that do not undergo sanitization. With our CPGs, we can identify such flows simply by checking the data dependencies of all the possible sinks. Figure 9 shows the WQL query for detecting taint-style vulnerabilities. Our goal is to find the sink nodes that depend on source nodes. To this end, we inspect the dependencies of each sink, checking if any of them depends on a sensitive source. If the obtained list is not empty, a vulnerability is flagged for each individual source-sink pair.

**Buffer overflows** occur when the program executes code that overflows a buffer. Buffer overflows are a common source of security vulnerabilities. They can lead to the leaking of sensitive information, the execution of arbitrary code, or the corruption of program data. Buffer overflows can occur in various contexts, such as when reading or writing to a buffer that is not properly sized. In the context of WebAssembly, buffer overflows can be caused by the improper handling of stack memory. Wasmati can be used to detect such vulnerabilities by analyzing the control flow and data dependencies of the program. The WQL query for detecting buffer overflows is shown in Figure 9. The query checks for the presence of a call to the malloc function that is followed by a call to the free function, which frees the memory segment allocated by the malloc call. If such a pattern is found, the query returns true, indicating the presence of a buffer overflow vulnerability.
foreach func in functions():
    nodes := [n in instructions(func) : (n.instType = "Call"
        ) && (n.label = "$malloc")];
    foreach n1 in nodes:
        descendants := [n in descendantsCFG(n1) : (n.instType
        -> "Call") && (n.label = "$free") && reachesDDG(n1, n, "Function", "$malloc")];
    foreach n2 in descendants:
        uafs := [n in descendantsCFG(n2) : reachesDDG(n1,
            n, "Function", "$malloc")];
    if (!uafs.empty())
        vulnerability("Use after free", func.name, 
            "$free");

Figure 8: Use-after-free WQL Query.

FOREACH func IN functions():
    sinkCalls := [n in instructions(func) : n.instType = "Call"
        ) && n.label in sinks &&
            ![e in n.inEdges : e.type = "DDG" && e.
                ddgType = "Function" && e.label
                in sources].empty()];
    foreach sink in sinkCalls:
        vulnerability("Tainted", func.name, sink.label);

Figure 9: Taint-flow WQL Query.

module pnm2png from the libpng library (CVE-2018-14550) [10]. The loop reads characters from a file and stores them in the buffer
token until the character read is one of those given in line 7. The problem is that the loop can have an arbitrary number of iterations,
while the buffer has a fixed size. As a result, we can trigger a buffer
overflow by picking a file containing a large enough string.

The WQL query used to find this vulnerability is given in the
appendix. In a nutshell, we have to search for loop instructions for
which: (1) there is a local variable $i$ representing an index being
incremented inside the loop; (2) there is a store instruction within
the body of the loop that depends on $i$ (buffer write operation);
and (3) there is no explicit loop exit (br_if) instruction that depends
on the result of a comparison operation directly involving the value
of $i$ (e.g. $i < BUF_SIZE$). For (1), we look for 132. add instructions
with two incoming DDG edges: one expressing a local dependency
on variable $i$ and another expressing a constant dependency on
the value to be added. For (2), we simply look for store instructions
that directly use the result of the 132. add instructions found in (1).
Finally, for (3), we search for br_if instructions that rely on the
result of a comparison operation involving the value of $i$. If no
such instructions are found, a vulnerability is flagged.

5.2 Other Query Back-ends

By developing multiple query engine back-ends, our primary goal
was to investigate the trade-offs that different query language
paradigms can offer regarding: i) expressiveness power, ii) conciseness and simplicity, and iii) query execution performance. After
developing and experimentally analyzing three query back-ends
that support imperative, logic, and database processing paradigms
above, we review the remaining three query back-ends, explaining their main
properties and how they can be used to query WebAssembly CPGs.

Native back-end: Wasmati comes with an API for users to implement
their queries directly in C++ and integrate them within the
Wasmati code base. To this end, a user simply needs to write a file containing a C++ function that describes their query and then
adds the query to a configuration file with all the queries to be
executed. A complete description of our query API is given in the
appendix. By writing queries natively, the user can leverage the high performance and expressiveness of C++. However, users have
to re-compile Wasmati every time they need to change or add a query to the system and they have to be acquainted with both C++
and the structure of the Wasmati code-base. The implementation
of some search patterns for Wasm code vulnerabilities (e.g., buffer
overflows) is also rather complex and prone to programming errors.

Neo4j: The CPG can be automatically loaded into a Neo4j [3] database
and running graph queries specified in Cypher, an SQL-like
language. Figure 10 shows the Cypher query for finding taint-style
vulnerabilities. The execution of lines 1 and 2 yields an interim table
of pairs, each consisting of a function node and one of its sink calls.
In lines 4-6, we look for source calls that reach any of the sinks
stored in the interim table via DDG function edges. Finally, in line
7, we return a table with the computed results, with each result cor-
responding to a taint-style vulnerability (source name, sink name,
enclosing function name). Neo4j relies on sophisticated planning
algorithms for maximizing the query execution performance. From
our experience, however, query planning works better for simpler
queries, as we have observed significant performance degradation
for complex queries involving multiple graph traversals.

Datatalog: The CPG can also be automatically loaded into Soufflé [20],
a state-of-the-art Datalog engine. Wasmati also provides a library
containing various predicates to reason about the structure of Web-
Assembly CPGs in a declarative fashion. For instance, it comes with
6 EVALUATION

This section presents our experiments to evaluate Wasmati. They mainly focus on answering the following questions:

1. Can security vulnerabilities in WebAssembly code be modeled and located using a CPG?
2. Does Wasmati find security vulnerabilities in WebAssembly code collected in the wild?
3. How well does Wasmati scale when generating CPGs from large real-world applications?
4. How do the different graph querying back-ends of Wasmati scale over CPGs generated from large applications?

Next, we present our experimental setup and main findings for each of these questions in a separate section.

6.1 Evaluation Using Annotated Datasets

In the first part of our evaluation of Wasmati, our goal is to assess the feasibility of modeling and finding security vulnerabilities in WebAssembly using CPGs. To achieve this, we implemented and executed the ten different queries described in §5 over four datasets containing programs written in C with known vulnerabilities. We compiled the datasets to WebAssembly using Emscripten 2.0.9 [12] with level 1 optimization and debug information. For our dataset selection, the vulnerabilities therein contained had to be properly annotated, even if the number of programs in the dataset was relatively small, as this allows us to access the ground truth and evaluate the detection effectiveness of our system. Next, we describe the four datasets that we used, containing a total of 110 C programs.

1. **Basic** has a total of 37 C programs compiled and created by us during the implementation and testing of Wasmati.
2. **Lehmann**: contains 7 programs from Lehman et al. [22]. The programs are attack primitives and end-to-end exploits. It includes a program using the vulnerable version of `pm2png` from `libpng` depicted in Figure 2, a remote execution code in NodeJs and arbitrary file write.
3. **STT**: is a repository of 47 C vulnerable programs from Binary Analysis School [36]. The programs are exploit exercises following the style of Capture the Flag.
4. **CWE**: is a list of “Weaknesses in Software Written in C” with a total of 19 example code snippets [11]. We removed the weaknesses where no query existed targeting it or the vulnerability in C is not ported to WebAssembly. We also removed duplicated code. One removed example is CWE-467 which flags the use of `sizeof()` on a pointer type.

| # | Query Description | LOC | NAT | WQL | N4J | DTL | TP | FP | P | TP | FP | P | TP | FP | P |
|---|-------------------|-----|-----|-----|-----|-----|----|----|---|----|----|---|----|----|---|
| 1 | Format Strings    | 24  | 10  | 19  | 139 | 5   | 0  | 7  | - | -  | -  | - | -  | -  | - |
| 2 | Dangerous Function| 14  | 8   | 5   | 137 | 7   | 0  | 7  | 1 | 0  | 1  | 0 | 10 | 1  | 0 |
| 3 | Use After Free    | 67  | 15  | 16  | 140 | 2   | 0  | 2  | - | -  | -  | - | -  | -  | - |
| 4 | Double Free       | 68  | 16  | 19  | 141 | 1   | 0  | 1  | - | -  | -  | - | -  | -  | - |
| 5 | Tainted CallIndirect| 55  | 12  | 13  | 139 | -   | -  | -  | - | -  | 5  | 0 | 5   | -  | - |
| 6 | Tainted Func-to-Func| 55  | 12  | 13  | 142 | 2   | 0  | 2  | - | -  | -  | - | -  | -  | - |
| 7 | Tainted Local-to-Func| 84  | 51  | 55  | 177 | 16  | 0  | 16 | 4 | 0  | 4  | - | -  | -  | 4 |
| 8 | BO - Static Buffer| 141 | 58  | 58  | 172 | 1   | 0  | 2  | 0 | 0  | 1  | 0 | 12 | 0  | 15|
| 9 | BO - Static Buffer (malloc)| 86  | 27  | 19  | 142 | 1   | 0  | 1  | - | -  | -  | - | -  | -  | - |
| 10 | BO - Loops       | 94  | 23  | 47  | 147 | -   | -  | -  | - | 1  | 0  | 1 | 2   | 0  | 2 |

Table 1: Query vulnerability report by dataset and LOC metrics for each querying approach. Acronyms: BO (Buffer Overflow), NAT (native, C++), WQL (Wasmati Query Language), N4J (Neo4J Cypher) and DTL (Datalog).

a predicate reachesDDG(X, Y, TYPE_DEP, LAB) to denote that the node Y is reachable from the node X via DDG edges with label LAB of type TYPE_DEP. Datalog queries are expressed as predicates for which the Datalog solver will try to find a model. When defining new query predicates, the user can leverage our library of CPG predicates which can result in a rather concise query specification. Figure 11 shows the Datalog query for finding taint-style vulnerabilities: we find a call to a source and a call to a sink using the predicates sources and call1 and then we require that the sink be reachable from the source using DDG function edges. On the other hand, Datalog is generally the less performing back-end.
Wasmati's recall for these datasets is 92.59%. This means that Wasmati contained programs written in C with known vulnerabilities. The results presented above show that these vulnerabilities persist in the corresponding WebAssembly binary after compiling the C code, and that Wasmati can successfully detect these vulnerabilities. To offer a comparison between Wasmati CPGs and the CPGs originally developed to detect vulnerabilities in C/C++ code [42], we decided to perform an evaluation of Joern [2], which is the open-source implementation of the original published work that is actively maintained. Note that it is also the basis of a commercial implementation of the original published work that is actively maintained, we expect it not to include the latest detection features or perform on par with its commercial version. We used the queries shipping with Joern, which are aimed at detecting the most common vulnerabilities in C code, and executed Joern directly on the C files of each dataset. Table 2 shows the aggregate results of Joern and Wasmati. From a total of 108 vulnerabilities in 110 programs, Wasmati correctly reported 100 vulnerabilities (TP) and reported 8 false positives (FP), while Joern correctly reported only 38 vulnerabilities (TP) and reported 65 false positives (FP). This further shows that CPGs can be successfully applied to WebAssembly for detecting vulnerabilities, with Wasmati achieving 92.59% recall and 92.59% precision, and Joern 35.19% recall and 36.89% precision when analyzing the original C files. We infer that this discrepancy in the results is directly linked to the coverage of the queries implemented by both tools and not necessarily mean that CPGs are less effective for C code. In Wasmati we focused on implementing comprehensive queries, while the open-source Joern implementation offers only 14 queries covering dangerous functions, format strings, buffer overflows, use-after-free, and other, corresponding to only 101 out of 108 total vulnerabilities in the datasets.

### 6.2 Vulnerability Detection in the Wild

In this second part of our evaluation, our goal is to assess Wasmati using WebAssembly binaries deployed in the wild. To this end, under ideal conditions, we would like to test Wasmati on a dataset that: i) contains a representative and large collection of real-world WebAssembly binaries, and ii) comes with ground truth annotations that allow us to determine whether or not the vulnerabilities detected by Wasmati are real. In the absence of such an ideal dataset, we used the dataset curated by Hilbig et al. [18]. It consists of 8,461 unique binaries collected from several sources (repositories, package managers, and websites), and it is not annotated.

We started by generating the CPGs for all the WebAssembly binaries of this dataset. From the 8,461 binaries, Wasmati has successfully generated CPGs for 7,879 (93.1%) binaries. Of the remaining 582 binaries, 561 (6.6%) failed mainly due to unsupported WebAssembly features in the binaries (e.g. threading, multi-return values, bad sections, etc.) and 21 (0.3%) exceeded the maximum allocated 16 GiB of RAM. These 21 programs had a mean size of 61 MiB. After gathering the generated CPG, we ran the 10 queries listed in Table 1. Next, we present the main findings of our analysis.

### Provenance of potentially vulnerable binaries: Table 3 shows the deployment location of WebAssembly binaries for which Wasmati detected at least one vulnerability. Percentage in relation to total number of collected binaries for that deployment location. Note that, in the dataset [18], the same binary might be collected from different sources, which leads to duplicates across lines in the table.
this information corresponds to the binary collection method). We see that the original dataset is heavily skewed, where 86.5% of all binaries of the dataset originate from Github. This helps explain why most vulnerable binaries detected by Wasmati (3,761) were originally found in Github repositories. We also observed that many of these binaries were obtained from repositories owned by security researchers, who collect selected WebAssembly binaries for research purposes. Beyond Github, Wasmati detects vulnerabilities in a considerable percentage of binaries that reach the production stage, such as real websites (web/httparchive), at the Node Package Manager (npm), in firef...
Comparison against related systems: To put Wasmati’s results in perspective, we compared it against the closest-related system in the literature named Wassail [35]. Wassail is a static taint analysis tool for WebAssembly programs focused exclusively on information flow analysis. In contrast to Wasmati, which generates full-blown CPGs, Wassail generates a much simpler graph data structure consisting only of the control flow graph (CFG) of the program followed by a data flow analysis propagation over the CFG. Wassail was written in OCaml and evaluated using the PolybenchC suite, which is composed of 30 C programs. To compare the performance between Wasmati and Wassail, we tested both systems against PolybenchC. The data structure computed by Wassail is comparable to the DDG in function of the graph’s size and can scale to larger programs.

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Note that Wassail is not a vulnerability scanning tool. Wassail was designed only to generate summaries that describe where the information can flow within functions. It offers no functionality that allows us to search for vulnerabilities in WebAssembly binaries. For this reason, we cannot use it as a baseline for evaluating Wasmati’s effectiveness in detecting the vulnerabilities analyzed in Table 1.

6.4 Query Execution Performance

Lastly, we measure the query execution time over the SPEC CPU 2017 benchmark to assess its scalability. Table 6 shows the execution times (in seconds) of the WQL queries described in Table 1 following the same numbering system. The first six queries are all similar in complexity, which translates into relatively similar execution times for the same binary. On average, a binary took less than 77 seconds to run all ten queries, totaling an execution time of around 22 minutes for all binaries. The larger binary, with 3.4M nodes and 44.1M edges, took about 8 minutes to complete all queries.

Figure 15 compares the execution times between the query back-ends. Neo4j and Datalog were not capable of executing all queries for the SPEC dataset before an established timeout of 10 minutes. In these cases, we capped the query execution time to the 10-minute mark, and proceeded to calculate the described averages. As it is clear from Figure 15 a), the native back-end outperforms all other back-ends, but at the cost of a harder query specification process. Datalog shows consistently high execution times, with the worse result being a 100x increase in query 7 when compared to the native back-end. Neo4j shows reasonable performance for simpler queries, such as queries 1 to 6, but quickly explodes in more complex queries, some of which did not finish before a timeout occurred. Finally, WQL shows significantly better performance than Neo4j and Datalog for most queries. Compared to native execution times, WQL shows, in the worst case, a 3x overhead, but the queries are much simpler to express and the execution times are still practical.
In Figure 15 b), six binaries show visible spikes in the execution times. These cases also include timeouts for Datalog or Neo4j. These are also the largest binaries of the SPEC dataset, which means that CPG analysis performance is directly related to the size of the graph, and Neo4j and Datalog are particularly less efficient at analyzing larger CPGs than the native and WQL back-ends.

7 LIMITATIONS
The precision of Wasmati’s results is bounded by the queries executed. As such, the ten queries discussed in Section 5 may not encode all the patterns that match a specific vulnerability type. For example, a taint vulnerability ceases to exist if proper sanitization is employed, but our taint queries do not check if common sanitization functions are called on the tainted data.

Wasmati can only analyze individual Wasm binaries. To uncover actual exploitable vulnerabilities in real applications, the analysis must also consider the application components that interact with the WebAssembly binary. An interesting direction for future work is to extend Wasmati to model JavaScript calls to exposed functions of a WebAssembly binary, as well as model accesses to the JavaScript array buffer used as the binary’s linear memory.

8 RELATED WORK
Empirical studies on WebAssembly: Some relevant studies characterize the performance of WebAssembly engines [31] as well as the prevalence [26] and security [18, 22] of WebAssembly code in the wild. The latter studies on security are of special interest to us, giving a comprehensive account of WebAssembly security vulnerabilities and how they can be exploited [22] and providing a dataset of real-world binaries that we use in our evaluation [18].

Program analyzes for WebAssembly: Since the proposal of the WebAssembly standard [32], several program analyzes have been designed for tackling the specificities of the language. Haas et al. [16] proposed a small-step operational semantics for WebAssembly together with a type system for checking the safety of stack-based operations. Later, Watt [39] mechanized both the semantics and the type system introduced in [16]. The proof infrastructure of [39] was then re-used to formalize and prove the soundness of CT-Wasm [41], a type-driven extension of WebAssembly for provably secure implementation of cryptographic algorithms. More recently, the authors of [40] introduced Wasm Logic, a program logic for modular reasoning about heap-manipulating WebAssembly programs. So far, most practical tools for WebAssembly analysis are based on dynamic analysis. Wasabi [23] is a general framework for instrumenting Wasm binaries and can be used to implement different types of dynamic analyzes. To the best of our knowledge, there are only three taint analysis tools for WebAssembly: TaintAssembly [14], the tool presented in [37], and Wassail [35], with the former two being dynamic and the latter static. Wassail implements a data flow analysis algorithm that has not been tailored for vulnerability detection. In particular, unlike Wassail, Wasmati specifically tracks constant and function dependencies, which are fundamental to reason about a large number of security vulnerabilities. Importantly, the authors of [35] do not demonstrate how Wassail can be used to enable a vulnerability detection tool. Wasmati is the first CPG-based framework for detecting vulnerabilities in WebAssembly code.

Code Property Graphs: CPGs have been applied to find SQL injection, XSS, and CSRF vulnerabilities in PHP applications [8, 30] and, most recently, for detecting CSRF vulnerabilities in client-side JavaScript [21], all on top of Neo4J’s backend. CPGs are at the core of CodeQL [1], a commercial tool for detecting security vulnerabilities in multiple programming languages, but not WebAssembly.

Joern [2] leverages CPGs to help developers detect vulnerabilities in C/C++ code. Although there is an open-source version of this tool, we did not use it for building Wasmati for three reasons: i) it is a very complex project, ii) Joern’s CPGs are generated from an intermediate code representation which hampers their portability and testing on various query back-ends, and iii) developing a custom DSL in C++ helps reduce the overheads of running the queries inside Joern, which runs on top of Scala, a JVM target language.

9 CONCLUSION
In this paper, we presented Wasmati, a static analysis tool for finding vulnerabilities in WebAssembly. It employs optimized techniques for generating CPGs for complex WebAssembly code, as well as four distinct back-ends for query execution. We implemented ten queries for each of the four execution back-ends, capturing different vulnerability types, and extensively tested Wasmati with four heterogeneous datasets. Wasmati can scale to large real-world applications and efficiently find vulnerabilities for all tested query types. Availability: Wasmati is publicly available at https://github.com/wasmati/wasmati.

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A. APPENDIX

A.1 Code Property Graph

| Property | Value |
|----------|-------|
| type     | AST   |
(a) AST edge.

| Property | Value |
|----------|-------|
| type     | CG    |
(b) CG edge.

| Property | Value |
|----------|-------|
| type     | CFG   |
| label    | Σ     |
(c) CFG edge.

| Property | Value |
|----------|-------|
| type     | DDG   |
| ddgType  | Σ_p  |
| label    | Σ_T  |
| valueType| Σ_V  |
| value    | R     |
(d) DDG edge.

Table 7: Edges.

### A.1.1 Node and Edge definitions.

- Σ = {false, true, default} ∪ Ν₀
- Σ_p = Σ ∪ FunctionName
- Σ_T = {Global, Local, Const, Control, Function}
- Σ_V = {i32, i64, f32, f64}

#### Table 8: Function node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Module |
| name     | {string} |
| index    | N₀    |
| nargs    | N₀    |
| nlocals  | N₀    |
| nresults | N₀    |
| isImport | [false, true] |
| isExport | [false, true] |

#### Table 9: Module node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Module |
| name     | {string} |

#### Table 10: Simple instruction node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Instruction |
| instType | Σ_T  |
| label    | {string} |
| nresults | N₀    |

#### Table 11: Simple node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Σ_T  |

#### Table 12: Constant node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Instruction |

#### Table 13: Labelled node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Instruction |

#### Table 14: Block node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Instruction |

#### Table 15: If node.

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Instruction |

| Property | Value |
|----------|-------|
| id       | N₀    |
| type     | Instruction |

Σ_T = {Br, BrIf, GlobalGet, GlobalSet, LocalGet, LocalSet, LocalTee, Call, BeginBlock}.
Table 18: Opcode instructions.

| Property   | Value       | Property   | Value       |
|------------|-------------|------------|-------------|
| id         | N₀          | id         | N₀          |
| type       | Instruction | type       | Instruction |
| instType   | Binary      | instType   | Compare     |
| opcode     | \{binop\}   | opcode     | \{relop\}   |

(a) Binary node.

| Property   | Value       | Property   | Value       |
|------------|-------------|------------|-------------|
| id         | N₀          | id         | N₀          |
| type       | Instruction | type       | Instruction |
| instType   | Convert     | instType   | Unary       |
| opcode     | \{cutop\}   | opcode     | \{unop\}    |

(c) Convert node.

| Property   | Value       | Property   | Value       |
|------------|-------------|------------|-------------|
| id         | N₀          | id         | N₀          |
| type       | Instruction | type       | Instruction |
| instType   | Store       | instType   | Store       |
| offset     | N₀          | offset     | N₀          |

Table 16: Load node.

Table 17: Store node.

Algorithm 1: AST Folding.

Input: Sequencial Instructions

Result: Folded Instructions

ST = ∅;  // Stack for instructions (LIFO)
RS = ∅;  // List for instructions (FIFO)

foreach inst ∈ Instructions do
    \( (\text{nargs}, \text{nresults}) = \text{GetArity}(\text{inst}); \)
    foreach \( i ∈ \{1...\text{nargs} \} \) do
        child = Pop(ST);
        AddEdge(inst.id, child.id, "AST");
    end
    if \( \text{nresults} = 0 \) then
        Append(inst, RS)
    else
        Push(inst, ST)
    end
end
return RS;

A.1.2 Transfer Functions.
Algorithm 2: DDG data flow generation for function f.

Input: Entry Node: Node Instructions of function f

Result: Map (instruction, rdef) for every instruction.

DEP = |
  g:  » Map for global definitions.
  1:  » Map for local definitions.
  st := 0:  » Lists of sets of definitions.
  l: := 0:  » Lists of labels.
|;
ST = { (Insts, DEP) }  » Stack (node, rdef) (LIFO)
res = ∅  » Map (instruction, inDep) to return.

while ST not empty do
  (inst, inDep) := Pop(ST);
  DEP := T(inst, inDep);
  if instType = Loop and (DEP ∪ res[inst]) = res[inst] then
    continue;
  else
    res[inst] := DEP;
    foreach child ∈ children(inst, CFG) do
      Push(ST, (child, RD));
  end
end
return res;

Table 19: Transfer Functions.

| Instruction Type       | Result Description                  |
|------------------------|-------------------------------------|
| t(const c, (g, l, st))  | (g, l, st := Cid(c, t))             |
| t(unop, (g, l, st := v0)) | (g, l, st := v0)                   |
| t(binop, (g, l, st := v0))   | (g, l, st := v0 ∪ v1)              |
| t(relop, (g, l, st := v0))   | (g, l, st := v0 ∪ v1)              |
| t(cvtop, t1, sx, (g, l, st := v0)) | (g, l, st := v0)                   |
| drop, (g, l, st := v0)     | (g, l, st)                         |
| select, (g, l, st := v0)   | (g, l, st := v0 ∪ v1)              |
| (local.set x, (g, l, st))  | (g, l, st := l(f, x))               |
| (local.tee x, (g, l, st := v0)) | (g, l[x → a0], st)                |
| global.get x, (g, l, st)   | (g, l, st := g(x))                  |
| (global.set x, (g, l, st := v0)) | (g[x → a0], l, st)                |
| (t.load, (g, l, st := v0)) | (g, l, st)                         |
| (t.store, (g, l, st := v0)) | (g, l, st)                         |
| memory.size, (g, l, st)    | (g, l, st := { })                   |
| memory.grow, (g, l, st := v0) | (g, l, st := { })                |
| (nop | br b | return), (g, l, st) | (g, l, st)                         |
| unreachable, (g, l, st)    | (g, l, st)                         |
| (block b, (g, l, st := v0, vj, lb := b + b_k)) | (g, l, st := v0, vj)   |
| (endLoop b, (g, l, st := v0, vj, lb := b + b_k)) | (g, l, st := v0, vj)   |
| (if b, (g, l, st := v0))   | (g, l, st)                         |
| (br if b, (g, l, st := v0)) | (g, l, st)                         |
| (br_table b' b_N, (g, l, st := v0)) | (g, l, st)                         |
| (call x, (g, l, st := a0 := a_i)) | (g, l, st := v_j)   |
| (call_indirect t, (g, l, st := a0 := a_i := c)) | (g, l, st := v_j)   |
A.2 Queries

```cpp
void VulnerabilityChecker::UseAfterFree() {
    for (auto func : Query::functions()) {
        for (auto const& item : config[CONTROL_FLOW]) {
            std::string source = item[SOURCE];
            std::string dest = item[DEST];
            auto sourcePredicate = Predicate().instType(InstType::Call).label(source);
            auto callSourceInsts = Query::instructions({func}, sourcePredicate);

            for (Node* callSource : callSourceInsts) {
                auto ddgEdgeCond = Query::ddgEdge(callSource->label(), DDGType::Function);

                Node* destNode = nullptr;
                auto destPredicate = Predicate()
                    .type(NodeType::Instruction)
                    .instType(InstType::Call)
                    .label(dest)
                    .EXEC(destNode = node)
                    .reaches(callSource, destNode, ddgEdgeCond);

                auto destInsts = Query::BFS({callSource}, destPredicate, Query::CFG_EDGES);
                for (Node* callDest : destInsts) {
                    Node* inst = nullptr;
                    auto uafPredicate = Predicate()
                        .inDDGEdge(callSource->label(), DDGType::Function)
                        .EXEC(inst = node)
                        .reaches(callSource, inst, ddgEdgeCond);

                    Node* parent = nullptr;
                    auto uafInst = NodeStream(callDest)
                        .BFS(uafPredicate, Query::CFG_EDGES, 1)
                        .filterOut(Predicate()
                            .instType(InstType::Call)
                            .label(dest)
                            .Or()
                            .EXEC(parent = node->getParent(0))
                            .TEST(parent->instType() == InstType::Call & & parent->label() == dest))
                        .findFirst();

                    if (uafInst.isPresent()) {
                        std::stringstream desc;
                        desc << "Value from call " << callSource->label()
                            << " used after call to " << dest;
                        vulns.emplace_back(VulnType::UaF, func->name(),
                            uafInst.get()->label(), desc.str());
                    }
                }
            }
        }
    }
}
```

Figure 16: Use-after-free in C++.

A.2.1 Use-after-free.
foreach func in functions():
    nodes := [n in instructions(func) : (n.instType = "Call") && (n.label in config["pairMalloc"])];
    foreach callMalloc in nodes:
        descendants := [n in descendantsCFG(callMalloc) :
                        (n.instType = "Call") && (n.label = config["pairMalloc"][callMalloc.label]) &&
                        reachesDDG(callMalloc, n, "Function", callMalloc.label)];
        foreach callFree in descendants:
            uafs := [n in descendantsCFG(callFree) : reachesDDG(callMalloc, n, "Function", callMalloc.label)];
        if (!uafs.empty()):
            vulnerability("Use after free", func.name, callFree.label);

Figure 17: Use-after-free in WQL.

MATCH (f:Function)-[:AST*1..]->(i:Instruction)
WHERE i.instType="Call"
AND i.label IN mallocs
WITH * MATCH (i)-[:CFG*1..]->(free:Instruction)
WHERE free.instType="Call" AND free.label IN frees
AND (i)-[:DDG*1.. {ddgType:"Function", label:i.label}]->(free)
WITH (free)-[:CFG*1..]->(uaf:Instruction)
WHERE (i)-[:DDG*1.. {ddgType:"Function", label:i.label}]->(uaf)
RETURN uaf.label as caller, f.name as function;

Figure 18: Use-after-free in Neo4j.

uaf(FUNC_NAME, SOURCE, SINK, Z) :-
    uafSourceSink(SOURCE, SINK), call(X, SOURCE, _, _), reachesFunc(FUNC_NAME, X),
    call(Y, SINK, _, _), ddgEdge(_, Y, SOURCE, "Function", _), reachesDDG(X, Y, SOURCE, "Function", _),
    reaches(X, Y, "CFG"),
    instruction(Z, _), ddgEdge(_, Z, SOURCE, "Function", _), reachesDDG(X, Z, SOURCE, "Function", _),
    reaches(Y, Z, "CFG")

Figure 19: Use-after-free in Datalog.
void VulnerabilityChecker::TaintedFuncToFunc() {
    std::set<std::string> sources = config.at(SOURCES);
    std::set<std::string> sinks = config.at(SINKS);

    for (auto func : Query::functions()) {
        auto query = Query::instructions({func}, [&](Node* node) {
            if (node->instType() == InstType::Call &&
                sinks.count(node->label()) == 1) {
                auto ddgEdges = node->inEdges(EdgeType::DDG);
                return Query::containsEdge(ddgEdges, [&](Edge* e) {
                    if (e->ddgType() == DDGType::Function &&
                        sources.count(e->label()) == 1) {
                        std::stringstream desc;
                        desc << "Source " << e->label() << " reaches sink "
                        << node->label();
                        vulns.emplace_back(VulnType::Tainted, func->name(),
                                          node->label(), desc.str());
                        return true;
                    }
                    return false;
                });
            return false;
        });
    }
}

Figure 20: Tainted source-to-sink in C++.

foreach func in functions():
    sinkCalls := [n in instructions(func) : n.instType = "Call" && n.label in sinks &&
                  ![e in n.inEdges : e.type = "DDG" && e.ddgType = "Function" && e.label in sources].empty()];
foreach sink in sinkCalls:
    vulnerability("Tainted", func.name, sink.label);

Figure 21: Tainted source-to-sink in WQL.

MATCH (f:Function)-[:AST*1..]->(sink:Instruction)
WHERE sink.instType="Call" AND sink.label IN sinks

WITH * MATCH (src:Instruction)-[:DDG*1..]->(sink)
WHERE src.instType="Call" AND src.label IN sources
    AND (source_call)-[:DDG*1.. {ddgType:"Function", label:src.label}]->(sink)
RETURN src.label as source, sink.label as sink,
    f.name as function;

Figure 22: Tainted source-to-sink in Neo4j.

A.2.2 Tainted function to function.
taintedFuncToFunc(FUNC_NAME, Y, SINK) :-
  sources(SOURCE), call(X, SOURCE, _, _), reachesFunc(FUNC_NAME, X),
  sinks(SINK), call(Y, SINK, _, _), reachesDDG(X, Y, "Function", SOURCE)

Figure 23: Tainted source-to-sink in Datalog.

foreach func in functions():
  loops := [n in instructions(func) : n.instType = "Loop"];
  foreach loop in loops:
    descendants := nil;
    vars := List();
    stores := [n in insts : n.instType = "Store" && ![descendants := descendantsAST(n).empty() &&
      ![child in descendants : child.instType = "Binary" && child.opcode = "i32.add"].empty() &&
      ![child in descendants : (child.instType = "LocalGet" || child.instType = "LocalTee") && vars.append(
        \( \rightarrow \) child.label).empty()]];
    foreach var in vars:
      nodes := [n in insts : n.instType = "BrIf" &&
        [descendant in descendantsAST(n) : descendant.instType = "Compare" &&
          [child in descendantsAST(descendant) : (child.instType = "LocalGet" && child.label =
            \( \rightarrow \) var) ||
            (child.instType = "LocalTee" && child.label = var)
            \( \rightarrow \)]]];
      if (!nodes.empty():
        vulnerability("BO Loops", func.name, loop.label);

bufferOverflow(FUNC_NAME, VAR, LOOP) :-
  loop(L, LOOP, _), reachesFunc(FUNC_NAME, L),
  binary(B, "i32.add"), reaches(L, B, "AST"),
  ddgEdge(X, B, VAR, "Local", _, _, _), ddgEdge(_, B, _, "Const", _, _),
  store(S, _), reaches(S, B, "AST"),
  brIf(BR, _), reaches(L, BR, "AST"),
  compare(COMP, _), reaches(BR, COMP, "AST"),
  ddgEdge(_, COMP, VAR, "Local", _, _).

Figure 24: Buffer overflow loops in WQL.

Figure 25: Buffer overflow loops in Datalog.

A.2.3 Buffer Overflow loops.
for (auto func : Query::functions()) {
    auto loops = Query::instructions({func}, Predicate().instType(InstType::Loop);

    for (Node* loop : loops) {
        auto insts = Query::BFS({loop}, Query::ALL_INSTS, Query::AST_EDGES);

        std::set<std::string> vars;
        auto stores = NodeStream(insts)
            .filter(Predicate().instType(InstType::Store)
            .child(0)
            .filter(Predicate()
            .instType(InstType::Binary)
            .opcode(Opcode::I32Add)
            .children(Query::AST_EDGES)
            .filter(Predicate()
            .instType(InstType::LocalGet)
            .Or()
            .instType(InstType::LocalTee)
            .forEach([&](Node* node) { vars.insert(node->label()); })
            .toNodeSet();

        for (auto var : vars) {
            auto brIfsNotEq = NodeStream(insts)
                .filter(Predicate().instType(InstType::BrIf)
                .child(0)
                .filter(Predicate().instType(InstType::Compare)
                .children()
                .filter(Predicate()
                .instType(InstType::LocalGet)
                .Or()
                .instType(InstType::LocalTee)
                .label(var)
                .Or()
                .instType(InstType::LocalTee)
                .label(var)
                .toNodeSet();

            if (brIfsNotEq.empty()) {
                std::stringstream desc;
                desc << "In loop " << loop->label() << ":";
                desc << ", a buffer is assigned without bound check.
                vulns.emplace_back(VulnType::BufferOverflow, func->name(), 
                    ", " desc.str();
                break;
            }
        }
    }
}

Figure 26: Buffer overflow loops in C++.
// Get loops
MATCH (f:Function)-[:AST*1..]->(loop:Instruction)
WHERE loop.instType="Loop"

// Get stores and vars
WITH *
MATCH (loop)-[:AST*1..]->(store:Instruction)-[argEdge:AST]->(storeArg:Instruction)-[:AST]->(var:Instruction)
WHERE store.instType="Store"
AND argEdge.arg=0
AND storeArg.instType="Binary"
AND storeArg.opcode="i32.add"
AND (var.instType="LocalGet" OR var.instType="LocalTee")

// Get add instructions in function
WITH *
MATCH (f)-[:AST*1..]->(add:Instruction)
WHERE add.instType="Binary"
AND add.opcode="i32.add"

// Check if var is being incremented with a constant
WITH *
MATCH (childConst:Instruction)<-[:AST]-(add)-[:AST]->(childLocal:Instruction)
WHERE childConst.instType="Const"
AND childLocal.label=var.label
AND (childLocal.instType="LocalGet" OR childLocal.instType="LocalTee")

// Check if breaks depend on store vars
WITH *
OPTIONAL MATCH path=(loop)-[:AST*1..]->(brIf:Instruction)-[:AST]->(compare:Instruction)-[:AST*1..]->(local:Instruction)
WHERE brIf.instType="BrIf"
AND compare.instType="Compare"
AND local.label=var.label
AND (var.instType="LocalGet" OR var.instType="LocalTee")

WITH path, f, loop
RETURN DISTINCT
CASE path WHEN path=null THEN f.name END AS function,
CASE path WHEN path=null THEN loop.label END AS loop;

Figure 27: Buffer overflow loops in Neo4j.
A.3 Query Infrastructure

| NodeSet | functions() | \(O(1))\) | Returns all the function nodes. |
|---------|-------------|------------|-------------------------------|
| NodeSet | child(NodeSet set, Index n, const EdgeType type) | \(O(V))\) | Returns the \(n\)’th child according to the edge type. |
| NodeSet | children(NodeSet set, EdgeCondition\& cond) | \(O(V))\) | Returns all the children following the edges according to an edge condition. |
| NodeSet | parents(NodeSet set, EdgeCondition\& cond) | \(O(V))\) | Returns all the parents following the edges according to an edge condition. |
| NodeSet | filter(NodeSet set, Predicate\& pred) | \(O(V))\) | Filters the node set according to the given predicate. |
| EdgeSet | filterEdges(EdgeSet set, const EdgeCondition\& cond) | \(O(E))\) | Filters the edge set according to the given predicate. |
| NodeSet | descendants(NodeSet set, Predicate\& pred, EdgeCondition\& cond) | \(O((N+E)/V))\) | Returns all descendants nodes following an edge condition and a predicate. |
| NodeSet | instructions(NodeSet set, Predicate\& pred) | \(O(N/V))\) | Returns all instruction nodes from the function nodes in the set. |

Table 20: Basic query API.

| Predicate\& <keyProperty>(Value value, bool equal = true) | \(O(1))\) | Compares the value from property `<keyProperty>` against the provided value. |
| Predicate\& inEdge(EdgeType type, std::string label, bool equal = true) | \(O(E))\) | Check if node contains and incoming edge with given type and label. |
| Predicate\& inDDGEdge(DDGType type, std::string label, bool equal = true) | \(O(E))\) | Check if node contains and incoming DDG edge with given DDG type and label. |
| Predicate\& outEdge(EdgeType type, std::string label, bool equal = true) | \(O(E))\) | Check if node contains and out-coming edge with given type and label. |
| Predicate\& outDDGEdge(DDGType type, std::string label, bool equal = true) | \(O(E))\) | Check if node contains and ot-coming DDG edge with given DDG type and label. |
| Predicate\& reachesIn(Node* src, EdgeCondition\& cond) | \(O(N + E))\) | Check if there is a patch from src following an edge condition. |
| Predicate\& reachesOut(Node* dest, EdgeCondition\& cond) | \(O(N + E))\) | Check if there is a patch to dest following an edge condition. |
| Predicate\& test(std::function<bool(Node*)> func) | \(O(func))\) | Tests the condition given by lambda function `func`. |

Table 21: Predicate API.

A.3.1 Native.

A.4 Evaluation Tables
### Table 22: CPG generation times and information from SPEC CPU 2017 binaries.

| Binary         | Source | Instruct. (k) | Size (KiB) | Nodes | Edges | Memory (MiB) | Time | Exported (MiB) |
|---------------|--------|---------------|------------|-------|-------|--------------|------|----------------|
| 500.perlbench_r | C      | 837.8k        | 1,964      | 879.0k | 2.5M   | 175.87       | 45.34s |               |
| 502.gcc_r      | C      | 2.9M          | 6,964      | 3.1M  | 9.6M   | 642.24       | 4min 15.97s |               |
| 505.mcf_r      | C      | 27.4k         | 56         | 30.0k | 89.0k  | 6.14         | 1.20s  |               |
| 508.namd_r     | C++    | 323.0k        | 636        | 343.0k| 813.0k | 64.05        | 7.62s  |               |
| 510.parest_r   | C++    | 1.0M          | 2,190      | 1.1M  | 3.5M   | 226.47       | 33.51s |               |
| 511.povray_r   | C++    | 385.4k        | 909        | 406.5k| 1.4M   | 90.06        | 4min 19.76s |               |
| 519.lbm_r      | C      | 13.4k         | 29         | 14.6k | 55.2k  | 3.36         | 1.39s  |               |
| 520.omnetpp_r  | C++    | 619.3k        | 1,524      | 658.0k| 4.3M   | 205.01       | 23.67s |               |
| 523.xalancbmk_r| C++    | 1.5M          | 3,404      | 1.5M  | 13.7M  | 587.35       | 58.53s |               |
| 525.ledcov_r   | C      | 233.0k        | 476        | 224.0k| 624.2k | 44.67        | 6.44s  |               |
| 525.x264_r     | C      | 283.6k        | 592        | 282.1k| 864.1k | 58.65        | 8.88s  |               |
| 526.blender_r  | C++    | 3.2M          | 9,944      | 3.4M  | 44.1M  | 1,735.99     | 4min 45.86s |               |
| 531.deepsjeng_r| C      | 53.0k         | 112        | 56.6k | 158.0k | 11.30        | 2.15s  |               |
| 538.imagick_r  | C      | 517.5k        | 1,216      | 552.5k| 1.6M   | 112.10       | 35.74s |               |
| 541.leela_r    | C++    | 118.8k        | 272        | 135.5k| 384.0k | 27.23        | 3.08s  |               |
| 544.nab_r      | C      | 55.6k         | 122        | 60k   | 172.6k | 12.13        | 2.85s  |               |
| 557.xz_r       | C      | 53.3k         | 136        | 57.8k | 185.8k | 12.29        | 10.37s |               |

Average per binary: 713.0k 1,797 747.6k 4.9M 236.17 57.79s 22.44

| Total          | 12.1M | 30,547 | 12.7M | 83.9M | 4014.91 | 16min 22.36s | 381.50 |

### Table 23: WQL execution time for each query over the SPEC binaries (in seconds). Darker cells represent higher execution times.

| Binary         | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | Total |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 500.perlbench_r | 5.72 | 6.13 | 5.53 | 5.22 | 4.41 | 6.04 | 0.09 | 27.18 | 6.18 | 5.66 | 72.17 |
| 502.gcc_r      | 17.93 | 22.93 | 17.32 | 16.59 | 21.11 | 17.70 | 0.40 | 89.02 | 19.70 | 27.35 | 250.05 |
| 505.mcf_r      | 0.15 | 0.17 | 0.17 | 0.16 | 0.17 | 0.22 | 0.02 | 0.88 | 0.15 | 0.33 | 2.41 |
| 508.namd_r     | 1.96 | 1.79 | 2.21 | 2.32 | 2.16 | 1.74 | 0.02 | 7.36 | 1.84 | 3.25 | 24.64 |
| 510.parest_r   | 6.49 | 6.76 | 7.07 | 7.29 | 6.31 | 6.95 | 0.15 | 37.23 | 7.54 | 10.73 | 96.52 |
| 511.povray_r   | 2.17 | 2.29 | 2.40 | 2.80 | 2.39 | 2.77 | 0.06 | 9.69 | 2.27 | 3.78 | 30.63 |
| 519.lbm_r      | 0.08 | 0.08 | 0.09 | 0.08 | 0.07 | 0.10 | 0.02 | 0.50 | 0.07 | 0.23 | 1.33 |
| 520.omnetpp_r  | 4.60 | 3.89 | 3.71 | 5.16 | 5.82 | 4.01 | 0.18 | 20.78 | 4.06 | 7.26 | 59.47 |
| 523.xalancbmk_r| 11.61 | 12.90 | 12.70 | 15.14 | 13.15 | 13.15 | 0.33 | 65.28 | 11.98 | 16.58 | 171.17 |
| 525.ledcov_r   | 1.26 | 1.10 | 1.39 | 1.34 | 1.38 | 1.43 | 0.03 | 6.34 | 1.32 | 1.98 | 17.59 |
| 525.x264_r     | 1.64 | 1.93 | 1.66 | 1.91 | 1.46 | 1.59 | 0.04 | 8.65 | 1.71 | 2.29 | 22.87 |
| 526.blender_r  | 32.81 | 41.00 | 36.17 | 32.18 | 35.70 | 41.28 | 1.08 | 194.12 | 32.11 | 41.53 | 487.98 |
| 531.deepsjeng_r| 0.30 | 0.39 | 0.39 | 0.33 | 0.28 | 0.37 | 0.02 | 1.89 | 0.34 | 0.88 | 5.19 |
| 538.imagick_r  | 2.81 | 3.00 | 2.96 | 3.88 | 3.98 | 2.67 | 0.05 | 14.72 | 3.34 | 4.70 | 42.11 |
| 541.leela_r    | 0.63 | 0.71 | 0.86 | 0.59 | 0.80 | 0.73 | 0.06 | 3.75 | 0.82 | 1.63 | 10.57 |
| 544.nab_r      | 0.28 | 0.35 | 0.38 | 0.41 | 0.34 | 0.29 | 0.02 | 1.79 | 0.31 | 0.98 | 5.16 |
| 557.xz_r       | 0.33 | 0.30 | 0.29 | 0.39 | 0.34 | 0.31 | 0.02 | 1.57 | 0.40 | 0.72 | 4.67 |

Average per binary: 5.34 6.22 5.49 5.52 6.01 5.96 0.15 28.87 5.54 7.64 76.74

Total: 90.75 105.72 93.38 93.79 102.12 101.37 2.60 490.76 94.15 129.88 1304.52