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Static detection of user-specified security vulnerabilities in client-side JavaScript

Graduation thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in de Ingenieurswetenschappen: Computerwetenschappen

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Abstract

Program defects tend to surface late in the development of programs, and they are hard to detect. The same goes for security vulnerabilities. This type of program defects is particularly important to detect as they might leak sensitive information or even compromise the system on which the program is executed.

A popular approach for analyzing programs is static analysis. Static analysis of a program is performed at compile time, implying that the program can be analyzed without being executed. Existing approaches using static analysis to detect security vulnerabilities in source code are often limited to a predetermined set of pre-encoded security vulnerabilities. Although these approaches are able to detect a decent amount of vulnerabilities and support a wide range of programs by default, they lack the means to be configured for vulnerabilities that are specific for the particular application domain of the analyzed program.

In this dissertation, we investigate how static analysis can aid in detecting application-specific security vulnerabilities. As these vulnerabilities are not general enough to be checked by tools that use a database of pre-encoded patterns, developers should be able to write rules that are specifically applicable to their program.

We present JS-QL, a tool for statically checking user-specified security vulnerabilities in JavaScript applications. The tool makes use of an embedded domain-specific query language built on top of JavaScript. JS-QL queries are based on regular path expressions, enabling users to express queries in an intuitive way. These expressions are a way of declaratively expressing queries on graphs as regular-expression-like patterns. In the context of this dissertation, regular path expressions are used to match user-specified patterns on the paths of an abstract state graph, which represents a program's possible run-time states and is generated as the output of performing static analysis.

We evaluated our approach by comparing our language with other languages for expressing security vulnerabilities in terms of expressiveness. We conclude that the combination of static analysis and regular path expressions lends itself well to the detection of user-specified security vulnerabilities.

Samenvatting

Tekortkomingen in programma's zijn moeilijk te detecteren en ze komen vaak pas laat aan de oppervlakte in het ontwikkelingsproces. Hetzelfde geldt voor beveiligingslekken. Dit soort van kwetsbaarheden is uitermate belangrijk om op te sporen, aangezien ze mogelijk geheime informatie lekken of er zelfs voor kunnen zorgen dat het systeem waarop het programma draait gecompromitteerd wordt.

Een populaire aanpak om programma's te analyseren is statische analyse. Statische analyse van een programma wordt uitgevoerd at compile time, wat betekent dat het programma kan geanalyseerd worden zonder het uit te voeren. Bestaande oplossingen die gebruik maken van statische analyse om beveiligingslekken op te sporen in broncode zijn vaak beperkt tot een voorafbepaalde set van voorgeprogrammeerde programmapatronen. Hoewel deze oplossingen een redelijk aantal kwetsbaarheden in programma's vinden, ontbreken ze een manier om geconfigureerd te worden om kwetsbaarheden te vinden binnen het domein van het geanalyseerde programma.

In dit proefschrift onderzoeken we hoe statisch analyse kan helpen om programmaspecifieke beveiligingslekken te detecteren. Aangezien deze beveiligingslekken niet algemeen genoeg zijn om gevonden te worden door tools die een databank van voorgeprogrammeerde patronen gebruiken, zouden ontwikkelaars de mogelijkheid moeten hebben om zelf patronen te schrijven die toepasbaar zijn op hun specifieke programma's.

We stellen JS-QL voor, een tool om op statische manier beveiligingslekken, gespecificeerd door de gebruiker, in JavaScript applicaties te detecteren. De tool gebruikt een embedded domein-specifieke querytaal die gebouwd is bovenop JavaScript. JS-QL queries zijn gebaseerd op regular path expressions die de gebruiker er toe in staat stellen queries uit te drukken op een intuïtieve manier. Regular path expressions zijn een manier om declaratief queries op graphs uit te drukken, gelijkaardig aan de notatie van reguliere expressies. Binnen de context van dit proefschrift worden regular path expressions gebruikt om patronen, gespecificeerd door gebruikers, te matchen tegen een abstract state graph die gegenereerd wordt als output van statische analyse. Deze graph stelt alle mogelijke run-time states voor van een programma.

We hebben onze aanpak geëvalueerd door onze taal op vlak van expressiviteit te vergelijken met andere talen waarin beveiligingslekken uitgedrukt kunnen worden. We besluiten dat de combinatie van statische analyse en regular path expressions zich goed leent tot het opsporen van beveiligingslekken die door de gebruiker gespecificeerd zijn.

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Chapter 1

Introduction

This dissertation investigates how static analysis can help developers to statically verify user-defined and application-specific security policies. Checking a program for security vulnerabilities using static analysis has as a benefit that the program does not have to be executed. Our thesis is that *a specification language based on regular path expressions can be used to effectively express patterns for detecting security vulnerabilities. These vulnerabilities are then searched for in source code by checking them against the output of the performed static analysis.*

Program defects tend to surface late in the development of programs, and they are hard to detect. The same goes for security vulnerabilities. This type of program defects is particularly important to detect as they might leak sensitive information or even compromise the system on which the program is executed. Existing approaches using static analysis to detect security vulnerabilities in source code are often limited to a predetermined set of pre-encoded security vulnerabilities. Although detecting a decent amount of vulnerabilities and supporting a wide range of programs by default, they lack the means to be configured for vulnerabilities that are specific for the particular application domain of the analyzed program. It therefore is important to be able to write succinct queries to test a program against *application-specific* flaws, as most programs differ in behaviour which makes it difficult to write a simple query or pre-encoded rule for a set of different programs.

We present JS-QL, an embedded domain-specific specification language based on regular path queries, built on top of JavaScript. This language enables expressing queries in the native JavaScript language in such a way that queries remain readable and that expressiveness is maximized. In our approach to detect security vulnerabilities, JS-QL is used in combination with static analysis to check *user-defined* queries against an abstract state graph, which is a the representation of a program's runtime behaviour resulting from the analysis.

1.1 Objectives and contributions

The use of Javascript for native and web applications is increasing. This has as consequence that malicious users get more creative and passionate about finding security vulnerabilities in these applications and that more of these vulnerabilities are exploited. Developers of applications should be armed with appropriate tools to find these vulnerabilities before their application gets deployed. We present such a tool that can be configured to detect vulnerabilities using a domain-specific specification language. Our contributions are the following:

1. We investigate which type of specification language is best suited to express security vulnerabilities and program characteristics in general. We believe that regular path expressions are a suitable means as they are expressive and easy to reason about. We evaluate our specification language by expressing multiple security vulnerabilities and comparing the resulting specifications to corresponding ones of existing work.
2. We present the JS-QL *domain-specific language*, a language built to express succinct and highly readable program queries. The application-specific nature of the queries written in the language together with the possibility for users to define these queries by themselves makes it a powerful aid in checking program characteristics and, more precisely, security vulnerabilities. In contrast to general program checkers, a much wider range of program characteristics can be detected.
3. Specifying security vulnerabilities is one thing, checking them against a program is another. To this extent, we have developed a *tool* to match the queries specified in JS-QL against JavaScript programs. The tool supports multiple types of queries, allowing developers to explore their program in several ways. A simple user interface handles all communication with the user, meaning that both input information (the query and the input program) and the output results (all found matches) are displayed in a single window. Although queries are evaluated through the user interface, compound queries can be written and saved in a separate file and are instantly available to the user.

1.2 Overview

Chapter 2 discusses the detection of security vulnerabilities. We first give an introduction to static analysis (Section 2.1). We discuss the basics of static analysis as well as a static analysis technique called abstract interpretation. Next, we review existing work for detecting generic vulnerabilities in programs (Section 2.2).

As the goal of this dissertation is to explore a way to express application-specific queries for detecting program vulnerabilities, we also describe some application-specific approaches to query for program characteristics and security vulnerabilities (Section 2.3). In this chapter we show that the approach that seems most apt for this thesis is to combine regular path queries with an abstract state graph.

In chapter 3 an overview of our approach is given. We sketch the architecture of our tool and briefly discuss what the roles of each component are (Section 3.1). As we traverse an abstract state graph to obtain program information, the user has to have knowledge of what information is contained in this graph. We go into greater detail about the information contained in each type of graph node in section 3.2. The language developed in this dissertation is a so-called internal domain-specific language (DSL) built on top of JavaScript. Section 3.3 discusses the benefits of domain-specific languages over general-purpose languages and compares internal domain-specific languages with external ones. Finally, this chapter also explains some of the design constraints for building a domain-specific language as well as design patterns used to implement the JS-QL language (Section 3.4).

The syntax, semantics and usage of the JS-QL language is explained in chapter 4. We describe all syntactic aspects of the language in section 4.1. Our implementation supports multiple types of queries, such as *existential* and *universal* queries, imposing different rules for a query to produce results. We also explain the difference between *forward* and *backward* queries, in section 4.2. The most important contribution of our approach is its support for user-defined and application-specific queries. In section 4.3 we describe how queries in JS-QL should be written by means of examples.

Chapter 5 describes how the tool is implemented and how components work together. We explain how the user interface is implemented and how it sends data to the DSL-layer. We further discuss how this data is processed as well as how the DSL is built. As the matching of the abstract state graph and the query pattern is the core of our tool, we invest in explaining how the matching engine works.

We report on the results of evaluating our approach in chapter 6 by expressing security vulnerabilities originating in related work. We checked if and how we can express these queries in JS-QL and evaluated the query verbosity, flexibility, expressiveness and readability. In this chapter we show that JS-QL is well-suited to specify different kinds of security vulnerabilities, but some specifications concerning dependencies in a program remain hard to express.

We conclude in chapter 7, and give an overview of the limitations of our approach and provide some topics for future research.

Chapter 2

Detecting security vulnerabilities

Definition 1. *A security vulnerability is a weakness in a product that could allow an attacker to compromise the system's integrity, availability and confidentiality.*

To check for these vulnerabilities we need a program representation containing specific information about the program to be able to answer questions about security vulnerabilities. The information we need in this dissertation is twofold:

1. *Control flow:* A program can contain many branches, loops and other control structures. We need to know the exact order of execution along each path in the program before we can make assumptions about security vulnerabilities. Therefore information is needed about which functions can be applied at a call site.
2. *Value flow:* Variables in JavaScript are mutable, so their values can change at any moment in a program. Value flow information tells us exactly what values an expression may evaluate to. This is very important w.r.t. security, as a variable bound to a harmless value may get assigned a harmful value somewhere in the program. From there on, that variable should be marked as a possible threat to the system.

A technique is needed to efficiently express security checks in the form of user-specified, application specific security policies. A naive way to examine programs would be to run them and keep track of any relevant information during execution. Not only would this be tiresome, we can also not guarantee that the program will ever terminate, that it terminates without errors, or that it will have the same outcome for different inputs. A better approach would be to analyze the program *without* having to run it. A field of research called *static analysis* accommodates for this.

This chapter describes how static analysis can be used to examine programs and how this analysis can be addressed to obtain information about specific parts

of a program. First, section 2.1 describes more precisely what static analysis is and why this technique is interesting in the context of this dissertation. Next, We discuss four approaches using static analysis to find generic vulnerabilities in programs in section 2.2. Finally, four application-specific approaches for checking security vulnerabilities are discussed. For these approaches we take a deeper look on how they query the information. We end this chapter by giving a brief conclusion.

2.1 Introduction to static analysis

Definition 2. *Static analysis is a technique for analyzing computer programs without having to execute them and still obtain useful results.*

Rice’s theorem states that the ability to decide non-trivial program properties is equivalent to the ability to decide whether a program halts (halting problem), which implies that deciding non-trivial program properties is undecidable. As proving non-trivial program properties is undecidable, static analysis focuses on the instances of the problem about which it can tell whether the program satisfies a property or not, and leaves other instances unsolved. In this way we can avoid the possible problems we might encounter using a naive technique (e.g. manually tracking information flow during execution). The results of the analysis may indicate program defects or can be used to prove certain properties of the program. The results of the static analysis will then be a useful set of approximate solutions. Figure 2.1 shows the main difference between a regular decider, which will always provide an exact answer, and a static analyzer.

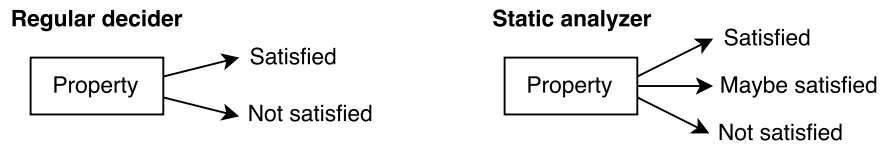


Figure 2.1: Proving program properties: Regular decider and static analyzer

Precision

Precision is very important in static analysis. Consider a static analyzer that concludes for each property that it is *maybe* satisfied. It is clear to see that there is no precision in this analysis, rendering it useless. We have to strive to attain enough precision to solve the maximum number of problem instances. For our approach, precision is of great importance as we need to minimize the amount of false positive and true negatives.

Speed

In the context of this dissertation, *speed* is less important for the analysis. As static analysis is decidable, it is guaranteed that the analysis will run in finite time, but gathering precise results is much more meaningful than the performance of the analysis itself.

A technique used for static analysis is *abstract interpretation*. This technique mimics interpretation of a program and allows to stay close to the original language semantics of a program without having to modify or instrument it to perform the analysis (in contrast to other static analysis techniques such as *symbolic execution*). This technique fits well for this dissertation, as we need to check for application-specific security vulnerabilities. It is thus a prerequisite that the semantics of the analyzed program lean as close to the original semantics as possible.

2.1.1 Abstract interpretation

Abstract interpretation is a static analysis technique used to reason about a program. It does this by interpreting an approximation of a program through abstraction of its semantics. A *sound* analysis can be performed and the precision of this analysis can be adjusted to the user's needs through various mechanisms. This increase in precision comes at the cost of a greater analysis running time.

Concrete interpretation

Abstract interpretation works in a similar way as normal program interpretation (i.e. *concrete interpretation*). The concrete interpretation of a program can be described as follows: A program e can be injected into an initial state s_0 , the entry point of the program. From this state other reachable states can be computed using a *transition function*, until after several transitions a final state is reached. If no such state is ever reached, the execution will not terminate and hence will run indefinitely. The output of interpreting a program like this is a possibly infinite trace of execution states. The layout of this execution trace might depend on the input of the program or other changing values, making it unsuitable for static analysis.

Applying abstraction

Abstract interpretation solves the problem of the uncertainty introduced by concrete interpretation by applying abstraction in order to compute a finite trace. Sets

of primitive values and addresses are *abstracted* to be made finite, resulting in something which is computable in finite time but less precise. Abstract interpretation is similar to concrete interpretation: A program is again injected, but this time into an *abstract state* \hat{s}_0 . A transition from one state to another is done through an *abstract transition function*. The difference between this and a regular transition function is that an abstract state can make multiple transitions to successor states. This is a consequence of the precision loss due to abstraction. Example 1 illustrates the difference between concrete and abstract interpretation.

Example 1. Figure 2.2 shows the concrete and abstract interpretation traces for `while(x < 5) { x--; }`. We assume that for the concrete case x is smaller than 5 when it reaches the code. The program will then never terminate, leading to an infinite execution trace. For the abstract case, we assume that x is abstracted. We see that in abstract state \hat{s}_3 the program can go to either \hat{s}_4 or \hat{s}'_4 , and that the (possibly infinite) `while` loop is represented as a loop in the abstract state graph. This finite representation of a program (which is actually an abstract state graph) proves to be useful to provide answers to non-trivial questions about the program.

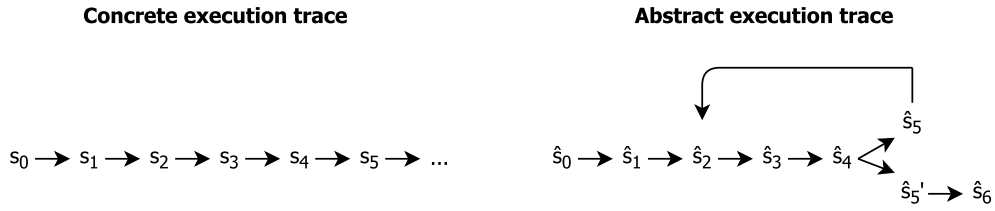


Figure 2.2: Concrete and abstract program execution traces

2.1.2 Abstraction

An *abstraction* \hat{X} of a concrete set X in abstract interpretation is a Galois connection between the power set of X ($\mathcal{P}(X), \subseteq$) and X itself (X, \sqsubseteq). The abstraction function α maps a concrete value to its abstract counterpart, whereas the

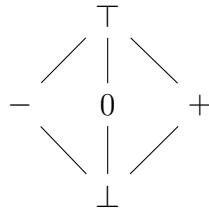


Figure 2.3: Partially ordered set of signs (complete lattice)

concretization γ function maps an abstract value to its concrete counterparts. Abstract values, sets and operations are generally indicated with a hat. Example 2 illustrates how abstraction works, and how it causes *imprecision* to occur.

Example 2. (Sign abstraction). A possible abstraction of integers \mathbb{Z} could be to map them onto the set of signs \widehat{Sign} . The set of signs forms a complete lattice with \sqsubseteq ordering, as depicted in figure 2.3. This abstraction could be used in an analysis to detect divisions by zero, for example. We can define the abstract and concretization functions as follows:

$$\begin{aligned} \alpha : \mathcal{P}(\mathbb{Z}) &\rightarrow \widehat{Sign} \\ \alpha(Z) &= \perp \text{ when } Z = \emptyset \\ &= 0 \text{ when } Z = \{0\} \\ &= + \text{ when } \forall z \in Z, z > 0 \\ &= - \text{ when } \forall z \in Z, z < 0 \\ &= \top \text{ otherwise} \end{aligned}$$

$$\begin{aligned} \gamma : \widehat{Sign} &\rightarrow \mathcal{P}(\mathbb{Z}) \\ \gamma(P) &= \emptyset \text{ when } P = \perp \\ &= \{0\} \text{ when } P = 0 \\ &= \mathbb{Z}^+ \text{ when } P = + \\ &= \mathbb{Z}^- \text{ when } P = - \\ &= \mathbb{Z} \text{ otherwise} \end{aligned}$$

The addition operator $+$: $\mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$ can also be abstracted to $\hat{+}$: $\widehat{\mathbb{Z}} \times \widehat{\mathbb{Z}} \rightarrow \widehat{\mathbb{Z}}$ following the rules of sign. Some examples:

$$\begin{aligned} \{0\} \hat{+} \{+\} &= \{+\} \\ \{-\} \hat{+} \{-\} &= \{-\} \end{aligned}$$

but for more advanced examples, we can easily see a loss in precision:

$$\begin{aligned} \{+\} \hat{+} \{-\} &= \{-, 0, +\} \\ \{0\} \hat{+} \{0, +\} &= \{0, +\} \end{aligned}$$

When applying the concretization function after the abstraction function, we observe that the result is less precise. Consider the negation function $f(N) = \{-n | n \in N\}$, which negates an integer. Applying the concretization function to an integer directly results in no loss of precision:

$$f(\{1\}) = \{-1\},$$

whereas applying it after the application of the abstraction function overapproximates the concrete value:

$$(\gamma \circ f \circ \alpha)(\{1\}) = \mathbb{Z}^+$$

\mathbb{Z}^+ is an overapproximation of $\{1\}$, conserving all properties that hold for $\{1\}$. The closer something is abstracted to its concrete value, the higher the precision of the analysis will be.

2.2 Support for generic vulnerabilities

Static analysis is often used by model checkers to verify if a program satisfies a set of properties (i.e. a specification of a program). These tools usually require additional information to be added to the program before being able to analyze it. The OWASP LAPSE+ plugin for Eclipse [31] for example requires the user to annotate all possible vulnerability sources and sinks in the source code. It then checks if there is information flow between a source and a sink.

2.2.1 Limitations

Although applicable to many programs, tools for finding general characteristics of programs is limited in several ways:

1. The set of problems that these tools can detect is often restricted and a lot of tools support detection for similar problems. Tools detecting bug patterns detect only the patterns that are pre-encoded in the tool. This implies that the tool only supports bug patterns that are pre-encoded and thus will most likely miss any bug pattern that isn't already encoded.
2. Poorly encoded patterns may miss bugs, making the analysis of the tool unsound.
3. Adding or extending functionality to existing solutions is often cumbersome and in most cases even impossible to do manually, which makes these solutions less useful for certain domain-specific programs, as these require a flexible tool.

To remedy these problems, a more practical approach would be to develop a tool which allows users to define by themselves what they wish to detect in a program. This approach would make the analysis *application-specific* and the detection rules would be *user-defined*. More about application-specific approaches can be found in section 2.3.

2.2.2 Existing analysis tools

The remainder of this section discusses the most popular static analysis approaches for model checking and finding generic code characteristics and vulnerabilities.

JOANA

The Java Object-Sensitive Analysis project (JOANA[35]) is an Eclipse plugin which checks for security leaks in Java programs. The tool supports all Java language features (except for reflection) and scales well for larger programs. The analysis used is flow-sensitive, context-sensitive, object-sensitive and lock-sensitive, minimizing the amount of false positives drastically. The types of security flaws JOANA is able to detect are:

1. *Confidentiality*: Information about sensitive values, like passwords or personal data, should in no case be conveyed to public outputs.
2. *Integrity*: The dual of confidentiality: In no way should unsafe program inputs alter secure data or influence sensitive computations of a program.

These flaws are detected by creating a system dependence graph (SDG) of the program on which information flow between sources and sinks is checked through program slicing. The SDG is an overapproximation of the information flow through the program. A benefit of this kind of graph is that it is able to detect direct (data) as well as indirect (control) dependencies. In order for the analysis to run, the user has to specify which parts of a program should act as sources and which should act as sinks. This is done by adding annotations to the source code. JOANA comes with a machine-checked soundness proof. Although JOANA is capable of finding dependencies between program points, it is limited in the amount of vulnerabilities it detects and there is no way to extend the tool to support more vulnerabilities.

Flawfinder

Flawfinder¹ is a tool for examining C/C++ source code and detecting security weaknesses. It comes with a database of well-known problems, such as buffer overflow risks and race conditions. The results of the performed analysis is a report of all found flaws with a corresponding security risk level. Although being useful to quickly check for security vulnerabilities, Flawfinder is not extensible and it is not aware of the semantics of the system under test. Control flow and data flow analysis are not supported by the tool, making it a naive approach.

¹<http://www.dwheeler.com/flawfinder>

FindBugs

FindBugs[19] is a static analysis tool for detecting bugs in Java programs. It detects many classes of bugs by checking structural bug patterns against a program's source code. These classes of bugs can be subdivided into three main classes: correctness bugs, dodgy confusing code, and bad practices. Recently, the Find Security Bugs plugin² was developed on top of Findbugs. This plugin can detect 80 different (pre-encoded) vulnerability types, among which are the top 10 OWASP security vulnerabilities. An example security violation detected by the plugin is the parsing of an untrusted XML file. The contents of this file might be malicious and thus may pose as a risk for the application. As the plugin is able to detect a wide range of bugs, the tool is well-suited to check for the most common security vulnerabilities. Nevertheless, only those vulnerabilities can be detected, and when a new class of security violations arises, there is no way to add detection rules for these vulnerabilities as a regular user.

CodeSonar

CodeSonar[21], developed by GrammaTech, is a proprietary source code analysis tool that performs a unified data flow and symbolic execution analysis for C, C++ and Java programs. GrammaTech claims to detect more code flaws than the average static analysis tool because they do not rely on pattern matching or other similar approximations. The approach CodeSonar uses is to compile source code and generate several intermediate representations, such as control flow graphs, call graphs and AST's. The tool then traverses/queries these models to find particular properties or patterns that indicate defects. Next to performing general checks, CodeSonar provides an C API which gives developers access to its intermediate representations of the compiled program. A user can then define custom checks on these representations. We did not verify the ease of use of these custom checks as we did not find any examples. The hybrid approach of CodeSonar (general checks *and* application-specified checks) preludes the next section of this chapter, which discusses approaches that support detecting application-specific vulnerabilities through user-defined queries and rules.

2.3 Support for application-specific vulnerabilities

An often encountered problem with tools supporting detection of generic vulnerabilities is that they often do not allow users to write their own rule or queries to find domain- and/or application-specific flaws. Even if some mechanism for

²<http://find-sec-bugs.github.io>

specifying user-defined rules is available, as in PMD³ for example, it often is cumbersome to write them in the tool’s input language. These limitations makes that these tools are often not very flexible, and it makes it hard to extend them.

In this section we discuss how putting the detection of application-specific characteristics and vulnerabilities in the hands of the application developer can facilitate the debugging process, by presenting some approaches which allow users to define their own program queries. Two main considerations for creating such a tool are (i) the way a program is represented and (ii) how the user is given access to this representation. The discussed approaches each have their own techniques to do so, and we elaborate on their advantages and disadvantages.

PQL

The purpose of the PQL language is to check if a program conforms to certain program design rules[27]. More precisely, it can be used to check the presence of sequences of events associated with a set of related objects. The language allows programmers to query for these types of sequences in an application-specific way, rendering it useful to detect design defects on a per application basis.

Either dynamic or static analysis can be used to solve these PQL queries, but only the latter is of interest for this dissertation. The static analyser uses a context-sensitive, flow-insensitive, inclusion-based pointer analysis. As PQL attempts to optimize results of the static analysis to use them in the dynamic analysis, the used analysis must be sound. The points-to information, together with the program representation, is stored as a collection of datalog rules in a deductive database called *bddbddb*. This is similar to the approach of GateKeeper[14].

Two interesting features of the PQL language are the support for subqueries and the ability to react to a match. The latter is only useful in the case we use dynamic analysis. Subqueries however add significant power to a language. In the case of PQL, they allow users to specify recursive event sequences of recursive object relations.

The actual matching of queries to these rules happens by first translating the PQL queries to the corresponding datalog queries. Once translated, the queries get resolved by the *bddbddb* system, after which the results are ready to be interpreted by the user. Since the analysis used is flow-insensitive, sequencing is not supported in such a way that the user can distinguish whether program point *a* happens before or after program point *b*. The same holds true for negation: no guarantees about ordering can be made, which means that one can not deduce whether an excluded event (i.e. a negated event) happens between two points in a sequence. Therefore, in order to maintain soundness of the approach, all excluded

³<https://pmd.github.io>

events are ignored.

A benefit of using Datalog is that it is very efficient and has way less overhead compared to full-fledged declarative programming languages. Storing an analysis/program as datalog rules may be efficient, but it is hard to get a good overview of the program by just looking at these rules. PQL closes the gap between the lack in readability of plain datalog rules and writing clean application-specific queries by introducing its own language. However, this language is verbose and the syntax is something the user has to get used to.

Pidgin

Pidgin[23] is a program analysis and understanding tool which allows users to specify and enforce application-specific security guarantees. The approach generates a *Program Dependence Graph* (PDG) of programs by using an interprocedural data flow analysis (object-sensitive pointer analysis). This graph contains all information about how data flows through a program. More precisely, each pair of connected nodes indicates that the second node of the pair depends in some way on the first node. Figure 2.4 shows a PDG of a guessing game.

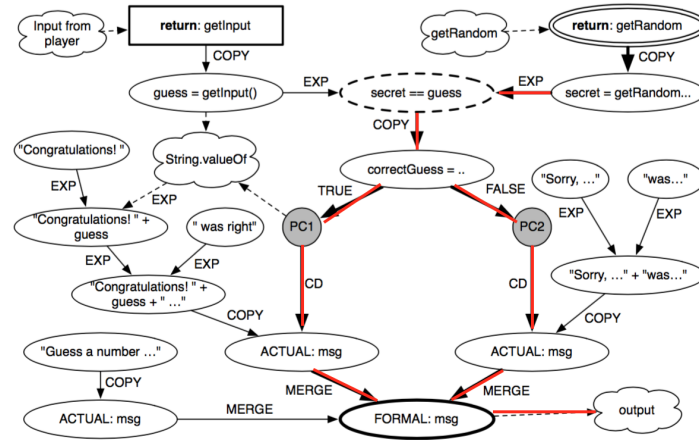


Figure 2.4: Program dependence graph of a guessing game

We can see that the value that flows to the output function indirectly depends on the value of the secret. This behaviour is usually undesirable, as information about the secret can be leaked to the output. This can be seen as a security violation and can be queried for in the Pidgin language. To this extent, the Pidgin Query Language (PidginQL) defines specialized constructs that allow the user to retrieve all relevant information from the PDG. As the program is represented as a graph, the approach specializes in detecting if there is information flow from one

node to another. An example of a PidginQL query is seen in listing 2.1. The usual approach to writing queries is as follows:

1. Specify the nodes between which information flow (from *source* to *sink*) needs to be detected and store them in variables. A *source* is a point in the program where sensitive information is available, whereas a *sink* is a program point where information may exit the program. This is done through the aforementioned constructs.
2. Specify *declassifier nodes*. These nodes act as sanitizers in a way that when information flows between a source and a sink and this information also flows through a sanitizer, then the flow is allowed.
3. Remove all declassifier nodes from the graph to make sure that the query won't detect false positives (i.e. no flows from source to sink through a declassifier node).
4. Check if there is any flow left between the specified sources and sinks.

```
1 //source, sink and declassifier
2 let source = pgm.returnsOf("getRandom") in
3 let sink = pgm.formalsOf("output") in
4 let declassifier = pgm.forExpression("secret == guess") in
5 //Remove declassifiers and check for flow
6 pgm.removeNodes(declassifier).between(source, sink)
7 is empty
```

Listing 2.1: A typical PidginQL query

The PidginQL language is expressive and powerful for detecting information flows. The language however lacks expressiveness when it comes to inspecting nodes. There are no constructs that allow the user to only find nodes with a certain name, for example. A second limitation is the result of queries. Most static analysis tools report all found violations, with more information about the violating code. PidginQL on the other hand just indicates whether there is flow or not (the `is empty` construct on line 7).

Metal

Metal[4] is a general analysis tool of programs for which a user has to write application-specific extensions called checkers. These extensions are then executed as a traditional dataflow analysis, but can be augmented in ways which are usually not supported by other more traditional approaches. Metal extensions are applied depth-first to the control-flow graph of a function. This flow graph is

computed from the AST of the program. By applying an extension depth-first, each program point down a single path in the graph is checked. This process is similar to pattern matching. Checkers in the Metal language consist of two parts: the actual code that describes the checker and a corresponding state machine. Metal distinguish two types of state machines: *Global* state machines and *variable-specific* state machines. The former is used for program-wide properties, whereas the latter detects object-specific properties.

Checkers are written by defining states between which the state machine can transition. When the current program point matches a pattern described in the current state of the checker, the state machine transitions to the next state and/or performs an action (usually printing a warning). When there is no match for the current program point, the state machine does not transition and the analysis continues with the next program point. Example 3 clarifies the approach.

Example 3. Figure 2.5 shows an global extension which checks for the double enabling of disabling of interrupts (`sti()` and `cli()` respectively). When enabling interrupts, the state machine transitions to the 'enabled' state. When enabling interrupts a second time, an error showing "Double sti" is printed. The same happens for disabling interrupts: when a user attempts to disable interrupts twice, or when the end of a path is reached when interrupts are still disabled (and thus the state machine is still in the 'disabled' state), an error will be printed.

```
.module macros.m

sm cli_sti {
  enabled:
    { cli(); } ==> disabled
  | { sti(); } ==> stop,
    { err("Double sti"); }
  ;
  disabled:
    { sti(); } ==> enabled
  | { cli(); } ==> stop,
    { err("Double cli"); }
  | $end_of_path$ ==>
    { err("Did not reverse"); }
  ;
}
```

Figure 2.5: A simple double enabling/disabling checker

The Metal language is an example of a readable query language. Describing the states in the order one wishes to detect them is in our opinion the sweet spot in query languages combining power, expressiveness, flexibility and readability.

JunGL

In contrast with other languages presented in this section, JunGL[37] is a scripting language to perform *refactorings*, based on pattern matching. Interesting in their approach is the specification of those parts of the code that need refactoring. In order to refactor some source code, the program first has to be represented in some way which is easy to access programmatically. JunGL does this by parsing the code into a uniform graph, initially containing only the information of the parsed AST. Lazy edges containing control flow information can also be added to the graph, but only when the refactoring needs this information. JunGL makes use of *path queries* to express a pattern to be matched.

For example, figure 2.6 shows the path query to find the path from a variable occurrence `var` to its declaration as a method parameter. This style of query denotation offers the exact amount of flexibility, readability and expressiveness needed to let developers express user-specified queries over a graph. An additional advantage of this type of queries is that no boilerplate code has to be written, as queries are self-contained.

```
[var]
parent+
[?m:Kind("MethodDecl")]
child
[?dec:Kind("ParamDecl")]
&
?dec.name == var.name
```

Figure 2.6: A typical JunGL path query

2.4 Conclusion

In this chapter we discussed what static analysis is and why it is important for detecting characteristics and vulnerabilities in source code. We have also discussed approaches that enable users to write clean and readable queries that define the patterns to be detected. From the discussion we conclude that the state of the art in static analysis has reached a point where tools supporting the detection of generic patterns often are not expressive and flexible enough for application-specific use. A solution to this problem is a tool and a language which allow users to specify their own, custom queries for an application. In this way, a database of pre-encoded vulnerability detection queries is not useful as the queries that are specified will mostly be too application-specific to generalize. We believe that expressing vulnerability queries (in the rest of this dissertation referred to as *security*

policies) is most readable and expressive using path expressions, as they they are close in form to a regular sentence consisting of consecutive pieces of code and states to be detected.

Chapter 3

Overview of the approach

This chapter gives an overview of our approach for building the JS-QL tool. For this tool we used the JIPDA [29] static analysis tool to generate an abstract state graph representing a JavaScript program. This graph contains control- and value-flow information, necessary to detect more complex security vulnerabilities. We have developed JS-QL, a querying language to effectively query for security vulnerabilities in JavaScript programs. The language is built as an internal domain-specific language on top of JavaScript. Our approach combines the JIPDA abstract state graph with JS-QL, resulting in a tool in which application-specific and user-defined security vulnerabilities can be specified and checked.

3.1 Architecture

The actual architecture of JS-QL is depicted in figure 3.1. The query engine takes as input (i) a flow graph and (ii) a query, written in the JS-QL language. The output will consist of tuples $\langle \text{State}, \text{Substitutions} \rangle$ for all paths on which a match for the query was found.

Program representation

For our approach, we used static analysis to represent a JavaScript program as a graph. Abstract interpretation, a static analysis technique, produces an abstract state graph when given a program as input. The graph contains information about control- and data flow, providing a rich source of information that can be extracted through some specification language and a querying mechanism.

There is an extensive body of related work on how logical programming can be used to represent and analyse programs [32, 25]. However, static analysis combined with a specification language leans more closely towards the implementa-

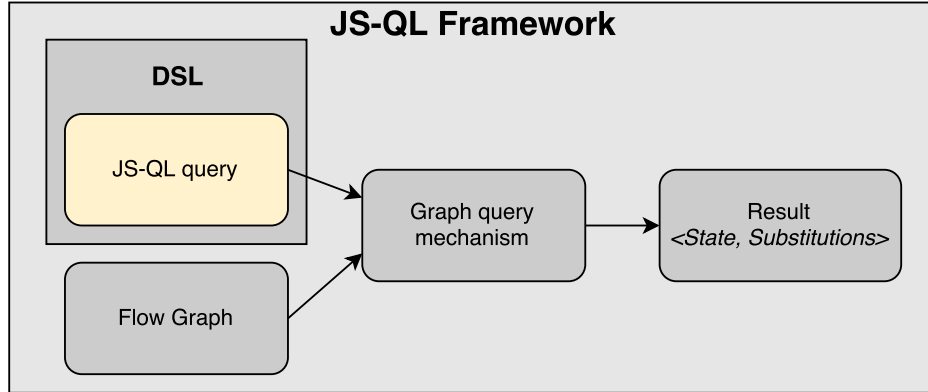


Figure 3.1: JS-QL architecture

tion of our system. As discussed in section 2.1, static analysis can be a means of representing implicit and explicit information about source code.

Query mechanism

Program querying depends on the way a program is represented and how queries are transformed into query-engine-friendly data structures. Our approach represents programs as flow graphs, and queries against these graphs need to be resolved. A suitable algorithm for solving queries is presented in [26], which enables us to query flow graphs directly. The internals of this algorithm will be discussed in greater detail in section 5.4. An alternative approach would be to use existing techniques such as *bddbddb* [39]. This technique matches queries expressed in Datalog against a database of rules representing the relations of an entire program. The overhead for this approach would however be too large, as we would have to transform the abstract state graph to Datalog rules.

Query language

With the JS-QL language, we offer an internal domain-specific language specialized in expressing queries corresponding to sequences of states in the flow graph. The language makes use of *regular path expressions*, which are expressions describing the path that needs to be traversed in a graph in a syntax similar to regular expressions. It is important that exploring and accessing information of a flow graph happens in a user-friendly way, as such graphs might be complex to understand. We believe that regular path expressions enable users to write clean and understandable queries.

3.2 Flow graphs for JavaScript programs

The need for detailed control- and data flow information in our program representation graph limits the types of graphs that can be used for our tool. The JIPDA abstract state graph, generated by statically analyzing source code through *abstract interpretation*, contains all the information needed to precisely express patterns to be detected in a program. The JS-QL tool uses the JIPDA graph as its program representation. This section takes an in-depth look at the JIPDA abstract state graph and the information it holds in its states. Other flow graphs, such as program dependence graphs [11], can be useful to track the flow of information between certain points in a program, but often lack more general information about program states, making them less qualified to use as our main program representation.

3.2.1 Information in an abstract state graph

Figure 3.2 shows part of a typical graph produced by JIPDA for a program containing a check for whether a number is equal to zero or not. As can be observed, the graph depicts all possible paths a program can traverse. Since the analysis in JIPDA is flow-sensitive, it is guaranteed that a state a on some path in the graph occurs before a state b on the same path if a occurs before state b in the program. This makes reasoning about patterns in a program much easier, since no false positives will occur with regards to the order of execution of states. The graph produced by the JIPDA analysis is also a flow graph, and more precisely maintains information about two types of flows:

1. *Data flow*: Information about what values an expression may evaluate to.
2. *Control flow*: Information about which functions can be applied at a call site.

We need this information to be able to make correct assumptions at certain states in a program, as illustrated in example 4.

Example 4. Consider the expression $f(x)$. Function f will be the function that is invoked. The value of f however may depend on other operations that occur before this function call, such as another function call. Therefore it is important to know which function(s) f may refer to, illustrating the need of control and data flow.

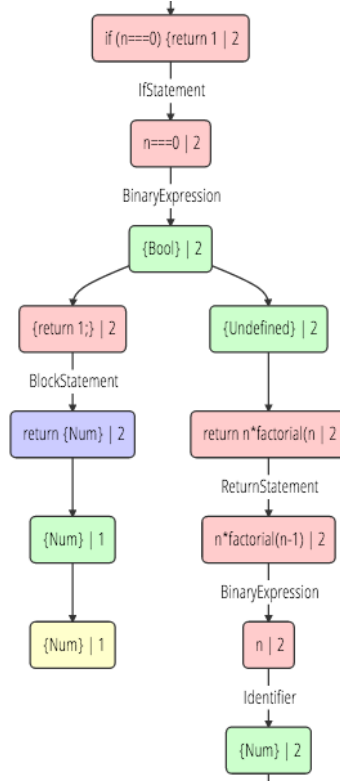


Figure 3.2: Example JIPDA abstract state graph

3.2.2 States of an abstract state graph

JIPDA uses Esprima [18] to parse JavaScript code and set up an abstract syntax tree (AST). This AST is the starting point for the analysis that JIPDA performs, hence information about the nodes from the AST is also contained in certain states in the resulting graph. The small-step semantics of a program are defined by an abstract machine that transitions between different states. The abstract machine is in eval-continuation style, indicating that a state is either an evaluation state or a continuation state. These states correspond to the states that can be seen in the abstract state graph. The states the machine can be in are described below:

1. *Evaluation state (red)*: Represents the evaluation of an expression of the program in the binding environment β .
2. *Continuation state (green)*: A state which indicates that the machine is ready to continue evaluation with the value it just calculated.
3. *Return state (blue)*: This is a special kind of continuation state, as it indicates the return of a function application. When the machine is in this state

it is ready to continue evaluation with the value calculated for the return of the function application.

4. *Result state (yellow)*: The final state of the graph, indicating the final computed value(s) of the program. This is also a special kind of continuation state. The machine and graph can have more than one result state, depending on the program's nature.

3.2.3 Attributes of the states

These states all contain relevant information about the point in the program they represent. The next part of this section discusses the different attributes that can be found in the states of the abstract state graph.

Node

Evaluation states contain information about the expression or statement they represent in the program. This information is stored in the form of an AST node, as obtained by the Esprima parser. Detailed information about the current expression or statement can be found in the properties of these nodes. Our approach makes extensive use of this information to find a match for a specified pattern along the graph. Note that node information is exclusively available in evaluation states. Example 5 depicts the layout of the AST-tree for a trivial JavaScript program.

Example 5. If we parse the following program

```
function answerToTheUniverse(arg) {  
  return 42;  
}
```

we obtain its corresponding JSON representation, listed in listing 3.1.

```
1 {  
2   "type": "Program",  
3   "body": [  
4     {  
5       "type": "FunctionDeclaration",  
6       "id": {  
7         "type": "Identifier",  
8         "name": "answerToTheUniverse"  
9       },  
10      "params": [  
11        {
```

```

12         "type": "Identifier",
13         "name": "arg"
14     }
15 ],
16     "defaults": [],
17     "body": {
18         "type": "BlockStatement",
19         "body": [
20             {
21                 "type": "ReturnStatement",
22                 "argument": {
23                     "type": "Literal",
24                     "value": 42,
25                     "raw": "42"
26                 }
27             }
28         ]
29     },
30     "generator": false,
31     "expression": false
32 }
33 ]
34 }

```

Listing 3.1: Parsed JavaScript program AST

The parsed source code is a list of nodes contained in the `body` property of the “program” AST node. This is the root node of the AST. Each node has its own *type* that distinguishes different kinds of expressions and statements. The example code in listing 3.1 shows that the parsed code is a “FunctionDeclaration” with its own `id`, `parameters`, `defaults` and `body` attributes. We observe that the attributes in turn can again be (a list of) nodes.

Binding environment and store

In JIPDA, variables point to addresses. The mapping of a variable to an address is called a *binding*. These bindings reside in a *binding environment* β . Each address maps to a value in the *store* σ , which acts as a heap. Being able to capture addresses and values in metavariables enables us to express and inspect data flow properties of programs. The first step for looking up a variable ν is to locate its binding in β . Next, the value of the variable can be looked up in the store by composing these two functions. The value of ν is given by $\sigma(\beta(\nu))$. This way of mapping variables to values allows us to reason about individual addresses, which is necessary because during interpretation multiple bindings to the same variable can exist simultaneously. Example 6 shows how a variable can be looked up.

Example 6. Listing 3.2 shows how a variable first gets a binding and is later looked up.

```

1  function f() {
2    //  $\beta$  contains a binding  $x \rightarrow \widehat{Addr}$ 
3    var x = 3;
4
5    //  $\sigma$  has an entry  $\widehat{Addr} \rightarrow \widehat{Val}$ 
6    // and the (set of) corresponding value(s) for x is returned.
7    return x;
8  }
9  var value = f();

```

Listing 3.2: Example of the binding environment and store workings

Value

The lookup of a variable through an address in the store results in the (set of) value(s) for that variable. Values can either be addresses or undefined. For continuation states, the value will represent the looked up or calculated values of an expression. A *return state*'s value is the set of possible values that will be returned. *Result states* contain the final values of a program.

Stack

The stack is a local continuation delimited by a meta-continuation. The *local continuation* is a (possibly empty) list of frames which acts as a stack of frames, with normal push and pop functionality. A *meta-continuation* is either empty or a stack address pointing to the underlying stacks in the stack store. Stack addresses are generated at call sites and thus represent application contexts. Useful information such as the call stack can be obtained by tracing out all reachable stack addresses in the stack store, starting from the context that is directly contained as meta-continuation in the current state. The traversal of the stack terminates when we encounter an empty meta-continuation, also called the *root context*. A program starts and terminates evaluation in this root context, provided that evaluation happens without errors. The root context corresponds to the top-level part of a program, the global namespace in JavaScript.

Although our tool does not provide stack traversal functionalities, basic properties of the stack (local continuation and meta-continuation) can be used and inspected to detect different kinds of states. For a function application, states corresponding with the start and end of the application will have the same local and meta-continuation. With this information, we can know the dynamic extend of

function applications for example. This makes it possible to check for expressions and statements within this dynamic extend, such as a recursive function call.

3.3 DSLs for querying graphs

Domain-specific languages are well-suited for querying graphs, as we can develop such a language to provide just the expressive power that is needed to match the states of a graph. For this dissertation we have developed JS-QL, an internal (or embedded [20]) domain-specific query language for querying abstract state graphs. We define domain-specific languages as follows:

Definition 3. A *domain-specific language (DSL)* is a programming language of executable specification language that offers, through appropriate notations and abstractions, expressive power focused on, and usually restricted to, a particular problem domain.

Definition 4. An *embedded or internal DSL* is a DSL built on top of a host language. This type of DSL inherits the infrastructure of its host language, and tailors it towards the domain of interest.

Definition 5. An *external DSL* is a DSL which comes along with a compiler which translates DSL programs into applications. The implementation of the compiler can completely be tailored to the DSL, allowing the developer of the language to freely choose the language constructs.

Domain-specific language is no new concept. Many programming languages that are now considered general purpose language started out as domain-specific languages. Cobol, Fortran and Lisp for example all came into existence as dedicated languages for solving problems in a certain area [9], but gradually evolved into the full fledged languages they are today.

Benefits over global-purpose languages

The key focus for DSLs are its focussed expressive power. The expressiveness of DSLs comes from the fact that they were created to solve a small set of problems. They offer a high-level set of mechanisms for the programmer to express his ideas for a particular application domain. A DSLs aim is to have the language focus specifically on those aspects and concepts that are relevant to a particular problem domain, hiding all boilerplate code that comes along with general-purpose languages (GPLs). However relevant for a wider area of domains, GPLs are often too general and have a set of operational baggage associated with them, making them unsuitable and too complex to write simple application- and domain-specific programs [16]. Benefits of domain-specific languages include:

- DSLs are application-specific. This allows users to express their ideas at the level of abstraction of the problem domain.
- DSL programs are concise, self-documenting and highly reusable [3].
- Increased productivity: Once the language design and implementation have finished, work becomes much more efficient as you don't have to write the boilerplate code of the GPL manually. In this way you can replace a lot of GPL code with a few lines of DSL code.
- Domain expert involvement: DSLs whose domain, abstractions and notations are closely aligned with how domain experts reason and express themselves, allow for a fluent integration between developers and domain experts. Domain experts can read, and possibly even write code in the language as they are not directly confronted with any implementation details.
- Programs are often expressed at a level of abstraction that is meaningful for the domain. This brings along that these programs contain domain knowledge and that they can be reused with few to no modifications.
- Improved code quality: Fewer bugs, better architectural conformance, increased maintainability. This is the result of the partially removing the programmers freedom and the avoidance of code duplication by providing DSL constructs.

Disadvantages

Some counterarguments for using a DSL are:

- The cost of designing, implementing and maintaining a DSL is high.
- The cost of educating DSL users is non-negligible.
- A DSL has limited applicability.
- It is difficult to find the correct scope for a DSL.

We argue that the costs for setting up a DSL do not weigh up against the benefits of a DSL. The high reusability alone makes up for the one-time investment of designing and implementing the language. When developing a language for a certain domain, naturally its applicability will be limited to that domain only, as this is the purpose of a domain-specific language. Finding the correct scope for a DSL might be cumbersome, but there is a large body of literature about specifying the domain of a problem [34] and the domain for DSLs [24, 15].

In contrast to the generic approach, the domain-specific approach to language design makes it possible to allow low-level system requirements to guide the design of the required high-level language features one wishes to incorporate into his language, instead of being required to use existing general-purpose designs. We therefore believe that a domain-specific language is the best pick for our specification language.

3.4 Design of an internal DSL for querying flow graphs

In this section we discuss the design process of our internal domain-specific language named JS-QL. Although internal DSLs are restricted by the syntax of their host language, they can make full use of the host language as a sublanguage, thus offering the expressive power of the host language in addition to domain-specific expressive power of the DSL. This expressive power along with not having to build a fully fledged compiler for our DSL are the main reasons we prefer the internal DSL approach above the external DSL one. We discuss the design constraints that influenced the design of our language as well as the implementation techniques and design patterns used.

3.4.1 Internal DSL design constraints

This section describe some factors that influenced the design of our specification language.

JavaScript as a host language

JS-QL has to be easily extensible as users need to be able to specify their own predicates and policies. To this extent, JavaScript is a well-suited language. The dynamic typing and optional function arguments made creating flexible predicates and policies a lot easier. However, because JS-QL is designed as an embedded language on top of JavaScript, it is also restricted to use only the constructs and syntax of the host language.

JavaScript `Objects` can be seen as dictionaries. The JIPDA graph states contain several fields that in turn can recursively contain other fields. The nature of the algorithm we use together with the structure of these states asks for a close mapping of states to query predicates. As JavaScript dictionaries are great for storing nested information, we use them as a mapping for states in JS-QL. Fields in a dictionary now have a one-to-one relationship with fields in a state, making the matching process for the algorithm less of a burden. JS-QL uses dictionaries in nearly all of its language constructs to map information from the state graph

to values or JS-QL variables. A disadvantage is that JavaScript dictionaries have keys that need to evaluate to a string at compile time. This is a limitation that affected the syntax of JS-QL, as will be discussed in section 4.1.6.

Flow graphs representing programs

The design of our language depends on the information that is contained in each state of the graph. The flow graph poses a constraint for our language, as sequences of states have to be expressed in a precise yet legible fashion. This has as a result that the language is set up as a fluent interface, enabling the user to specify a number of states separated with a simple dot. We can thus say that the type of graph helped shape the JS-QL language.

The query environment

A final constraint was the need of an environment where queries can be expressed and evaluated against the flow graph. We opted to extend the existing environment of the JIPDA analysis with support for (i) writing queries and (ii) checking these queries against the flow graph, as this is more user-friendly than using the built-in browser console. It also would be tiresome to specify queries in one place and the input program elsewhere, as this would imply that every time a change to the program or the query has to be made, at least one separate file has to be modified. This is clearly not an optimal solution.

3.4.2 DSL implementation techniques and patterns

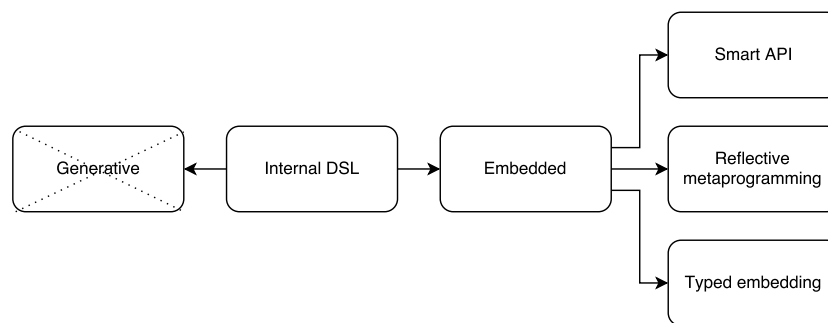


Figure 3.3: Internal DSL implementation techniques

Figure 3.3 shows the different kinds of implementation techniques for internal DSLs, as specified by [13]. Our DSL doesn't generate any code, so we won't discuss generative internal DSLs. for the JS-QL language, we use a *smart API*

approach, as it is ideal for our domain. By chaining methods in our DSL we can specify which states we want to encounter along the graph in a clearly specified order. We can define smart API as follows:

Definition 6. *a **smart API** is an API that is readable, easy to use and does not need boiler plate to work properly.*

Readability is key for DSLs. Implementing a fluent interface is a way to improve readability and make a smart API. To this extend method chaining is a popular technique: It can be implemented by making the output of one method flow naturally as the input of another. Benefits are that a series of invocations in the DSL feel more natural and that it expresses the series of actions you want to perform or detect in the problem domain.

Alternative approaches

Alternative approaches for implementing embedded internal DSLs are reflective metaprogramming and type embedding. We can already rule out type embedding, as this is only used for statically typed programming languages (JavaScript is dynamically typed). Reflective programming on the other hand would have been a good approach if we needed to add information to the states of the flow graph. However, JIPDA states are self-contained (they contain all necessary information) and they thus do not need additional individual functionality or information.

Used DSL design patterns

Combining a smart API with several carefully chosen DSL design patterns[12] result in the concise and easily readable language that JS-QL is today. The remainder of this section elaborates on the chosen design patterns.

Method chaining

Method chaining is a principle that allows methods to be specified one after another, and it is the bread and butter of our specification language. This approach offers a fluent interface to the user with the aim to write readable queries and avoid coding mistakes. The ability to express a state one wishes to encounter as a chained method to states discovered earlier in the graph allows to build very readable queries.

Example 7. Consider the query: `G.skipZeroOrMore().functionCall()`. It is obvious that this code is intuitive: `G` is the entry point of our language, which indicates the start of a query. We then search for a path in the graph that contains

a function call somewhere down that path. This is expressed by `skipping` zero or more states until a function call state is encountered.

Literal map

A literal map provides provides the functionality to let the user specify detailed key-value pairs. Specifying that one wishes to find states is often too general. To this extent literal maps can be used to express which types of states we want to match and what information we want to capture in (meta)variables.

Example 8. `functionCall({name: 'f', arguments: '?args'})`. The literal map, enclosed in curly braces, indicates that only function calls with name `f` need to be matched and that the arguments of the matched state need to be captured in metavariable `?args`.

Object scoping

Object scoping encapsulates the language in such a way that the effects of the language only reach within the scope of this object. The example for the method chaining design pattern is also applicable for the object scoping pattern. A single entry point `G` is created for queries, limiting the impact of the query that object. This pattern remedies two JavaScript flaws: Global namespace pollution and malicious code injection. Potentially malicious code will only harm the `G` object, which is contained in some sort of sandbox.

Deferred evaluation

Deferred evaluation postpones evaluation of certain expressions, such as function calls. Some queries in JS-QL contain definitions for extra properties and filters. The information for these filters and properties is often not available at compile-time of our language. Deferred evaluation is used as a technique to delay the evaluation of those filters and properties until the matching process in the back-end has collected enough information. Our tool handles this by creating thunks for filters and properties and unwrapping these thunks when the matching engine needs to evaluate them. By the time the evaluation happens, all variables should be bound in these thunks in previous matching steps.

Example 9. Consider a metavariable `?val` which captures a value of an assignment. If we only want to match assignment states with a value greater than 2, we have to create a thunk for the filter function `>` with arguments `?val` and 2. We can not discard states with `?val` greater than 2 immediately, as we don't know which value will be bound to `?val` at compile time.

Delimiter directed translation

The delimiter directed translation design pattern imposes that statements in the DSL are separated by a delimiter. These statements then are evaluated from left to right separately. As method chaining is used as a means to set up the JS-QL fluent interface, all methods are separated by a dot (the delimiter). Each method separated by this dot gets separately translated internally into a representation that is easier for our backend to process.

Newline separators

Finally, the newline separators design pattern is incorporated in our DSL. This design pattern allows users to enter newlines between parts of their code. This greatly improves the readability and can split a program up in logical parts. Our DSL supports newlines in queries. This can be very useful to separate different states or sequences of states. Consider an example in which we only want to find assignments to variables `a` and `b`. Code can then be divided in two distinct parts, as in example 10.

Example 10. JS-QL code can be split up in logical parts thanks to its support for newline separators.

```
1 .assign({leftName: 'a'}) //first logical part
2 .or()
3 .assign({leftName: 'b'}) //second logical part
```

Listing 3.3: Newline separators

3.5 Existing DSL approaches for querying graphs

In this section, we describe some existing approaches for querying graphs. We describe four external DSL approaches and three internal DSL approaches. The latter gave us inspiration to build our own JS-QL internal domain-specific query language.

3.5.1 External DSLs

Many DSLs come along with a compiler which translates DSL programs into applications. These kinds of DSLs are called *external* DSLs. the compiler is also called an application generator[5], whereas the DSL is the application-specific language. The main advantage of external DSLs is that the implementation of the compiler can completely be tailored to the DSL. The DSL in turn is restricted in

no way with regards to notation and primitives because its syntax is independent of any underlying host language. The remainder of this section discusses existing work about external DSLs used for graph traversal and graph querying.

StruQL

StruQL is the query language behind the Strudel system[10]. The language is built to support the retrieval and construction of data for web sites. This data is represented as *data graphs* and originates from external sources, the integrated view and the web site itself. These data graphs depict web sites as graphs in which nodes represent web pages or atomic values and labelled edges which interconnecting nodes. These edges then represent the links or attribute values that connect two nodes. The language enables users to create and query data graphs, but the real power of StruQL lies in its ability to express regular path expressions. This allows for very flexible queries describing the paths about which information needs to be accessed in great detail. It also allows to compute the transitive closure of an *arbitrary 2n-ary* relation, meaning that it can compute all reachable nodes from a certain node for any input graph.

GraphQL

GraphQL[17] is a query language for querying graph databases. The language uses a graph pattern as a basic operational unit. These graph patterns consist of a graph structure and a predicate on attributes of the graph. GraphQL introduced the notion of formal languages for graphs. This is useful for composing and manipulating graph structures and is used as a basis of the graph query language. The core of the language is a graph algebra in which the selection operator is generalized to graph pattern matching and a composition operator is introduced for rewriting matched graphs. In terms of expressive power, the language is contained in Datalog. This means that every query in GraphQL can be converted to a Datalog query. The language allows users to express concatenation, disjunction and recursion, allowing users to write dynamic queries. They address the NP-completeness of subgraph isomorphism by using neighborhood subgraphs and profiles, joint reduction of the search space, and optimization of the search order.

ASTLOG

ASTLOG[7] is a query language for syntax-level C/C++ program analysis and is well suited to construct anchored patterns to match tree-like structures. Syntax-wise, the language is built as a Prolog variant, but instead of transforming an entire

program into a database of Prolog rules, it is able to match *objects* to queries directly. These objects are being made available through a C/C++ compiler frontend which provides an interface to the syntactic/semantic data structures built during the parse of a program. Among the available objects are the AST nodes of a program. These nodes can then be examined and queried by user-defined predicates in a similar fashion as one would do in Prolog. This allows for application-specific composable predicates.

Lorel

The Lorel language[1] was designed to query semistructured data. This kind of data can be seen as a graph with complex values at internal nodes, labeled edges and atomic leaves. The language’s syntax resembles that of OQL (*Object Query Language*), but has two additional features: (i) A coercion mechanism for value/object comparisons and (ii) powerful path expressions. Coercion is needed for semistructured data, as two objects may represent the same data in different ways. Lorel introduces *general path expressions*, a way to define label completion and regular expressions in paths. Regular expressions are supported through `.,+,?,*,()` and `|`, label completion is done as in SQL, namely with the `%` symbol.

3.5.2 Internal DSLs

This section describes three internal DSLs, two for graph traversal and one that illustrates the flexibility and expressiveness of embedded DSLs. The terms internal DSL and embedded DSL both have the same meaning in the rest of this dissertation and both refer to the type of DSL that is embedded in a host language.

Gremlin

the Gremlin [33] language is a graph traversal machine. The machine traverses graphs according to a user-specified traversal, making use of so-called traversers. These traversers can be seen as ‘workers’ who walk through the graph, maintaining information about the path they have already taken and the current graph node they are in. The language is meant to be implemented as an internal DSL in a host language that supports *function composition* and *functions functions as first-class entities*. The Gremlin language has an *instruction set* of about 30 steps and each query is a sequence of these steps (i.e. a path). Querying graphs through paths is a well-known approach, but the Gremlin machine also supports nested paths in which each nested path is a graph traversal on its own. Queries are transformed into traversals, so each traversal can be made application-specific. Gremlin present 9 different traversals, including a recursive and a domain-specific one.

Dagoba

Dagoba¹ is an in-memory graph database system written in JavaScript. The chapter about Dagoba in the *500 Lines or Less*² book provides an elaborate explanation on how to create a flexible, easily extensible internal DSL. The language is built as a fluent API, and explains which mechanics (such as lazy evaluation) go hand in hand with this kind of language representation. The developers of Dagoba also describe how they interpret the language and define some optimizations of the system, mainly through query transformers.

A little language for surveys

A Little Language for Surveys [8] explores the use of the Ruby programming language to implement an internal domain-specific language. It checks how well the flexible and dynamic nature of the language accommodates for the implementation of a DSL for specifying and executing surveys. Two key features of the Ruby programming language are exploited because these features especially support defining internal DSLs: the flexibility of the syntax and the support for blocks. Function calls for example are easily readable, since the braces surrounding the arguments can be omitted and the argument list can consist of a variable number of arguments. They make extensive use of the fact that entire blocks can be attached to method calls. These blocks are passed unevaluated to the called method, enabling *deferred evaluation*. In addition to these features, the meta-programming facilities of Ruby make it possible to read a DSL program and execute it in the contexts specified by that program. A two-pass architecture is used, splitting up the parsing and interpretation of the program. This is common practice for internal DSLs.

3.6 Conclusion

In this chapter we discuss our approach for building the JS-QL tool. We described the architecture of the tool and discussed each component. As our approach uses the JIPDA abstract state graph as a program presentation, we described the information that can be found in this graph. JS-QL is an embedded domain-specific language. In this chapter we motivated the use of an embedded DSL, and we describe the design constraints and design patterns that influenced the language. Finally, we provided an overview of existing DSL approaches for querying graphs.

¹<http://aosabook.org/en/500L/dagoba-an-in-memory-graph-database.html>

²<http://aosabook.org/en/500L>

Chapter 4

JS-QL: An internal DSL approach for querying flow graphs

In this chapter we present the JS-QL tool. The tool offers the possibility for developers to write application-specific queries to check for certain program properties. More specifically, the tool offers a solution to developers for testing their applications for vulnerabilities by writing and enforcing security policies for these applications. We use the JIPDA abstract state graph as the program's representation, and we check all queries against the graph. The tool consists of three main parts:

1. *The JS-QL query language*: Short for **J**ava**S**cript **Q**uery **L**anguage. It is a domain-specific language in which users can express different kinds of security vulnerabilities. An overview of the language is given in section 4.1.
2. *The matching engine*: The engine is the core of the tool. It matches user-defined queries against states in a JIPDA abstract state graph, capturing and unifying relevant program properties.
3. *The graphical user interface*: The user interface provides the infrastructure for the developer to interact with the tool. It contains a section where users can specify the input program and a security policy, a graphical component representing the abstract state graph corresponding to the input program and a visual and textual representation of the query results. The textual representation allows developers to inspect the captured variables, a useful feature when these variables are compound data structures. The user interface is depicted in figure 5.1.

The abstract state graph obtained from the JIPDA analysis is a suitable starting point to inspect a program for certain characteristics and security vulnerabilities.

In chapter 3 we motivated our choice to design an internal DSL to query for specific (sequences of) states in this graph, with the aim to discover program patterns that might lead to violations of user-defined security policies. The language constructs are designed to facilitate the specification of patterns that must be detected.

The remainder of this chapter presents all facets of the JS-QL language: Section 4.1 discusses all constructs of the language and gives an in-depth explanation on how to correctly use them. As different security vulnerabilities require different traversals of the state graph, more than one type of query is needed. We discuss the difference between several query types in section 4.2. In order to have an effective specification language, we must enable the user to create compound queries out of the available language constructs. Section 4.3 shows how this can be done in the tool.

4.1 The JS-QL query language

In this section we discuss the syntax and semantics of the JS-QL language. The examples in this section are kept simple to demonstrate how each construct works. For more advanced queries and security vulnerabilities, we refer to chapter 6.

4.1.1 The entry point

JS-QL is an internal DSL, meaning that it is embedded in a host language, and that the host language has to provide an entry point from where we can start using JS-QL. In our approach the `G` object, short for **G**raph, is the entry point. This implies that all query patterns in JS-QL will start from this object. Example 11 shows how `G` can be used.

Example 11. Listing 4.1 shows a query where the first state of the graph is matched, starting with entry point `G`.

```
1 //Match the first state of the graph
2 G.state()
```

Listing 4.1: Matching the first state starting from entry point `G`

4.1.2 State

The `state` construct is the single most basic element of the language. It matches any state in the graph, but does not provide other information. Nevertheless it is the most important building block of the language, as it can be used to construct higher-level queries and predicates.

Keywords

States can be made more precise and expressive by parametrizing them with *state keywords*. We will first give a short overview of what information is available in which states. To get a more detailed explanation on what each piece of information represents, we refer to the section about flow graphs (3.2). Table 4.1 indicates what information is available in which type of state. The table also shows which keyword is used to represent the information contained in the states.

Legend		
Evaluation state	E	
Continuation state	K	
Return state	R_t	
Result state	R_s	
All states	A	

State property	Available in states	Keyword
Node	E	node
Meta continuation	A	kont
Local continuation	A	lkont
Binding environment	E	benv
Store	A	store
Value	$K R_t R_s$	value
Identifier	A	_id
Successors	A	_successors

Table 4.1: Information in the states of the abstract state graph

To improve readability, JS-QL provides four extra constructs that are semantically almost equivalent to the regular `state` construct. `evalState`, `kontState`, `returnState` and `resultState` are included in the language to match only those specific kinds of states. Note that the tool also supports the usage of the identifier and successors of a state, but it is very uncommon to use them, as they are semantically irrelevant to queries. An identifier is a unique value, used to distinguish different states. The identifier of a state would only be relevant when a query is matched in that exact state. When this is the case, the state gets marked in the visual graph representation and all query information is then contained in that state. Successors also contain few additional information, as all direct successors of a state are already made explicit in the state graph.

Parametrizing a state

Variables in JS-QL are strings starting with a `?`. The fact that we use strings comes from the embedded nature of our language: If we were to specify variables as literals, the host language would complain that it does not recognize the literal. This is illustrated in example 12.

Example 12. The query on line 2 of listing 4.2 depicts a JS-QL query that captures the `type` property of the node in variable `'?nType'`. If we omit the quotes around the variable, the syntax would not be recognized by the host language, as seen on line 4.

```
1 //Capture the 'type' property of the node in variable '?nType'
2 G.state({ node : { type: '?nType' }})
3 //Exception: ?nType is not recognized by the host language
4 G.state({ node : { type: ?nType }})
```

Listing 4.2: Defining variables in JS-QL

As the example indicates, JS-QL deconstructs state properties as nested key-value pairs. In this way, each part of information can be captured in a variable. The key indicates the property to be matched whereas the value can be one of three things:

1. A *variable*. When placing a variable as the value in a key-value pair in JS-QL, that variable gets bound to the key's corresponding value in the JIPDA state. The `?nType` variable in the example above gets bound to the value of `type`, which in this case corresponds with the type of the AST node for the currently matched state.
2. A *nested map* which further deconstructs the current property. The example above does this by further deconstructing the `node` property of a state (which represents the corresponding AST node) in order to reach the `type` of that node and store it in a variable. This is primarily used to match specific AST nodes.
3. A *literal*. Literals are mostly used to filter the states to be matched. When applying this to the example above, the `'?nType'` variable could be replaced by the literal `'ExpressionStatement'` for example. Note that the question mark (`?`) is omitted. The resulting query would then only match a state having the `type` of its corresponding AST node equal to `'ExpressionStatement'`.

States can thus be parametrized by matching the keywords displayed in table 4.1 as keys with values that can be variables, literals or nested maps. Because queries

matching single-state patterns are not yet security policies, JS-QL enables users to specify sequences of states as a query. When checking the state graph against this query, all states in the query pattern need to be matched one after another. When a state in the query pattern is encountered that does not match the current state in the state graph, the matching process is aborted for the current path that is investigated in the state graph. Consider the query in listing 4.3:

```

1 G.state({ node : { type: '?t' } })
2 .state({ node : { type: '?t' } })

```

Listing 4.3: Unification in JS-QL

Variable `?t` occurs twice in the query. This can be done on purpose to achieve *unification*. Unification means that two variables with the same name have to contain the same value. After executing the first line, the first state in the graph is matched (assuming that it has the `node` property) and the variable `?t` is bound to the type of the node. The matching engine then proceeds to the next state in both the query and the state graph. If the next state again has the `node` property with the same type as already bound to `?t`, the unification process has succeeded and the whole query will match. If the node type of the next state isn't equal to the value already bound to `?t`, or if that state doesn't have a `node` property, there is no match. The results of a successfully matched query will be the set of all possible *substitutions*, together with the identifier of the state where the last element of the query matched. Figure 4.1 gives a simplistic visual representation of this process.

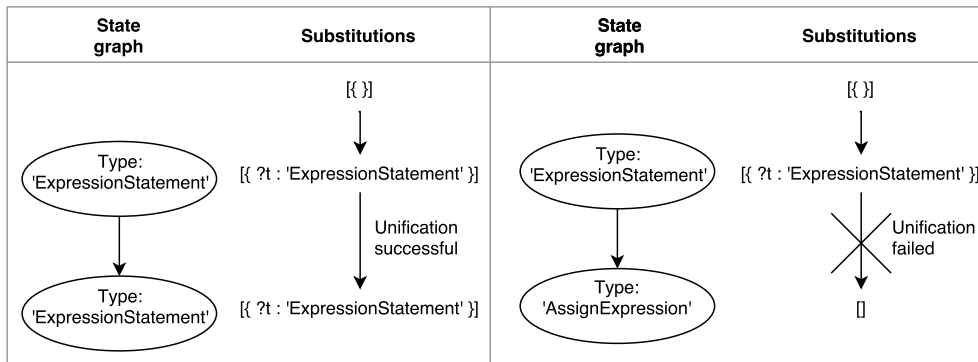


Figure 4.1: Visual representation of the unification process

All queries presented up until now match the state graph from the beginning of the graph only. This behaviour is often undesirable as a developer usually wants to detect a pattern *somewhere* in his code, not necessarily at the beginning. To

resolve this, JS-QL combines techniques from regular expressions with a special built-in construct, the *wildcard*.

4.1.3 Wildcard

A wildcard can be described as a placeholder for 'things of which the value can be anything'. A `wildcard` serves the sole purpose of matching any state it gets compared with. In other words, another name for this construct would be `skip`, as it skips a state in both the query (the `wildcard` state itself) and the abstract state graph (the state the wildcard gets matched with). When talking about states in a query pattern, both `state` and `wildcard` match this definition. `wildcards` act just like regular `states` in a query, meaning that they only match *1* state in the state graph.

Skipping multiple states

It is very unlikely that a developer knows exactly after how many states a violation would occur, so simply enumerating wildcards followed by the state to be matched would typically be a very tiresome effort. We therefore need to be able to specify that we wish to skip *zero or more* states before matching the following state in the query pattern.

This is where the power of regular expressions is useful. Just like regular expressions, JS-QL supports the use of both the Kleene star (`star`) and the Kleene plus (`plus`) operators. In our language, the `star` and `plus` constructs are both placed *after* the state(s) they are applied to. Placing `star` behind a state indicates that that state can occur *zero or more* times at the current position in the state graph. The semantics of `plus` are very similar, except for the fact that the state has to occur at least once.

Just like with regular expressions, pieces of a pattern can be surrounded by braces. Left and right braces in JS-QL are denoted by `lBrace` and `rBrace` respectively. The default behavior of both the Kleene star and Kleene plus operators is to apply them to the state that occurs right before it. If any Kleene operator has to be applied to multiple states, these states have to be wrapped in braces in JS-QL. The different uses of the Kleene operators are depicted in example 13

Example 13. Listing 4.4 shows the differences in using the Kleene operators with and without braces. Lines 1 and 2 are semantically equivalent, as the braces on line 2 only contain 1 state, a `wildcard` in this case. Lines 3 and 4 on the other hand are semantically different. The query on line 3 matches all but the first states in the state graph, whereas the query on line 4 matches every other state in the graph, starting from the second state. The combinations of `wildcard().star()` and

`wildcard().plus()` are so commonly used in JS-QL, that a special construct is created for each of them: `skipZeroOrMore()` and `skipOneOrMore()` respectively.

```
1 G.wildcard().star() // Equal to G.skipZeroOrMore()
2 G.lBrace().wildcard().rBrace().star()
3 G.wildcard().state().plus()
4 G.lBrace().wildcard().state().rBrace().plus()
```

Listing 4.4: Kleene operations differences

4.1.4 Disjunction

Sometimes when writing a query, more than one state qualifies as a match. JS-QL provides the `or` language construct, which enables users to specify that 1 state in the state graph can be matched by multiple states in the query pattern. Consider a simple language in which we want to detect all uses of a variable `v` in binary arithmetic expressions. When using a variable in a binary arithmetic expression, the variable can be on either side of the operator. A naive solution to query for all uses of `v` would be to first launch a query that finds all occurrences of `v` on the left-hand side, followed by a query that detects all occurrences on the right-hand side. If we then were to match all occurrences of `v` on the left- and right-hand side of arithmetic expressions, we could write a query as in listing 4.5.

Example 14.

```
1 G.skipZeroOrMore()
2 .lBrace()
3   //Left-hand side with name 'v'
4   .state({node: { type: 'BinaryExpression',
5                  left: {name: 'v'}}})
6   .or()
7   //Right-hand side with name 'v'
8   .state({node: { type: 'BinaryExpression',
9                  right: {name: 'v'}}})
10 .rBrace()
```

Listing 4.5: The JS-QL disjunction operator

This query first skips zero or more states, starting from the beginning of the graph. It then matches a state (`evalState` would be equally correct) with a `node` property of type `'BinaryExpression'`. Remember that the `node` property of evaluation states contains the AST information for the current expression. Because of this, the `left` and `right` properties of the `BinaryExpression` are again nodes that can be further deconstructed. The `or` construct splits the query in two different query paths. One path will try to match the pattern specified before the

construct, whereas the other path searches for matches for the pattern specified after the `or`. The same rules apply w.r.t. braces as for the `star` and `plus` operators. For the first path, we deconstruct the left property of the node and match its name with the literal `v`. This automatically filters out all states for which this condition doesn't hold. What remains is a match for each state for which the condition holds. The same is done for the second path, with the only difference that the name of the right node now has to be equal to `v`.

4.1.5 Referring to the current object

The `this` JS-QL keyword is an implicit property that is made available for each deconstructable map in the language, representing the entire object by which it is encapsulated. The keyword is designed to allow the user to capture a piece of information in a nested map into a variable, while allowing the user to further deconstruct that map. The use of `this` is demonstrated in example 15.

Example 15. When examining example 14, we notice that little relevant information is available as a result of the query. A more detailed result should contain the actual node or even the entire state that was matched, so we could inspect it further. Listing 4.6 gives an updated version of the relevant code from the previous example. In this version, the `?thisNode` variable will be bound to the node of the matched state. Without the `this` keyword, an object could only be stored in a variable by assigning it directly in the nested map, as seen on line 6. This would prohibit the user from further deconstructing the current object, making the language less expressive.

```
1 //...
2 .state({node: { this: '?thisNode',
3               type: 'BinaryExpression',
4               left: {name: 'v'}}})
5 //...
6 .state({node: '?node'})
```

Listing 4.6: Using the `this` keyword

4.1.6 Specifying additional properties

JS-QL has a built-in keyword `properties`, which can be used to obtain more information from already bound variables. Sometimes it can be useful to capture extra information about already matched variables. Doing so via a separate keyword in the language, exclusively designed for this purpose, has two advantages. First of all, it enhances the readability of queries. Queries with deeply nested maps can quickly become confusing to read and bothersome to modify. Secondly,

it opens up for opportunities to make the language even more expressive. Expressing properties can be done in two ways, as described in the following two sections.

The `prop` function

`prop` is a function in JS-QL to which the user can pass which kind of information he wish to obtain and from which variable properties need to be obtained. The first argument of `prop` is the function that needs to be applied when the matching engine processes the query. The arguments of this function are all other arguments that were passed to `prop`. Example 16 shows how to use the `prop` function. We have to defer the evaluation of the function passed as a first argument to `prop` because at compile-time the values of the variables are not yet known (as no matching has happened). This function, in the example, `'memberOf'`, can be a user-specified function or a built-in function. As for now, JS-QL only has three built-in functions that work on variables, and all three require that variable to be of type *Array*:

1. *length*: This function can be used as: `prop('length', '?arr')`, where `?arr` is a variable with a value of type *Array*. The function then returns the length of the array bound to the variable.
2. *at*: This function takes 2 additional arguments: A variable containing an array, and an index `i`. The resulting value is the `i`th element of the array.
3. *memberOf*: This function takes a variable containing an array `arr` as an argument and expands the current substitution set, so that for each element in `arr` a new substitution set is created with that element appended to it.

Properties as attributes of variables

Another way to define properties is by simply specifying which attribute of a variable one wishes to capture. Line 6 of example 16 shows how the `'name'` of the `'left'` attribute of `?dec` is bound to `?decName`. Declaring a new property variable is done similarly for both ways of defining properties: The key of the map should contain the variable name to be declared, whereas the value should be the property specification. This order of key-value pairs is different from all other notations in JS-QL. Because the host language (JavaScript) does not allow function calls to be keys in maps, it restricts the syntax JS-QL.

Example 16. This example matches all states of the state graph that declare variables. These declarations are captured in `?decls`. Next, for each declaration, a

new substitution set is generated by the 'memberOf' function. Each substitution set now contains a variable `?dec` bound to an element of the `?decls` array. The substitution set before the execution of line 5 would look like

```
[{?decls : [dec1, dec2]}],
```

and would afterwards look like:

```
[{?decls : [dec1, dec2], ?dec : dec1 },
  {?decls : [dec1, dec2], ?dec : dec2 }].
```

The name of the declaration in each substitution set is captured in `?decName`. Finally, for each substitution set the characters of the declaration name are converted to upper case.

```

1  G.skipZeroOrMore()
2  .state({
3      node:{ declarations: '?decls' },
4      properties:{
5          '?dec'      : prop('memberOf', '?decls'),
6          '?decName'  : '?dec.left.name'
7          '?decNameU': prop(function(a){
8                          return a.toUpperCase();
9                          }, '?decName')
10
11      })

```

Listing 4.7: Specifying additional properties in JS-QL

It is important to keep in mind that only the variables that are already bound can be used in properties. This implies that the order of the keywords in a query is important for the semantics of the query. If we were to switch the `node` and `properties` keywords of the above query, an error would occur because the `?decls` variable wouldn't be available to use in the properties section.

4.1.7 Filtering states

JS-QL provides the `filters` keyword to enable the user to specify filters for queries. A filter can be any function, predefined or specified by the user, that returns a boolean value. When returning true the pattern can be matched further, otherwise the matching process aborts and no match for the current path in the state graph is found. Filters in JS-QL work very similar to properties, except that they act as guards who filter out states that don not satisfy certain conditions.

A filter is declared through the `cond` JavaScript function (similar to `prop` for properties), and takes a filter function as a first argument. All other arguments are passed as the arguments to the filter function. As no variables have to be stored for filters, the value of the `filters` keyword is a JavaScript array, instead of a (nested) map. Example 17 illustrates how filters are useful in JS-QL queries.

Example 17. JavaScript allows the declaration of multiple variables in one declaration statement, e.g.:

```
var a = 1, b = 2;
```

Assigning more than one variable on the same line may be considered as a bad practice, as it is harder to maintain and less error-prone. A query can be written to detect all violations of this pattern, by storing the length of the declarations in a variable and checking if the length of the variable is larger than 1. Only the states for which this filter is satisfied will be contained in the results of the query. Listing 4.8 illustrates this example.

```
1 G.skipZeroOrMore()
2 .state({
3     node:{declarations: '?decls'},
4     properties:{
5         '?length' : prop('length', '?decls')
6     },
7     filters:[
8         cond('>', '?length', 1)
9     ]
10 })
```

Listing 4.8: Filtering for multiple declarations

4.1.8 Data flow in JS-QL

Data-flow analysis is a technique for gathering information about the possible set of values calculated at various points in a computer program. Support for data flow opens up to write a whole new class of queries. As JavaScript is a dynamic language, any variable can be assigned to any other variable. This phenomenon is known as *aliasing*, and is very common in the language. As already discussed in chapter 3, JIPDA stores the addresses and values of variables in the `store`. As a consequence of precision loss of abstract interpretation, reference types can point to multiple addresses in the store, whereas primitive types can point to multiple values.

Looking up addresses and values

Variables and functions can be looked up in JS-QL using the `lookup` keyword. The value-part of this keyword is again a map with the names of the variables to lookup as keys, and the variable names that need to be bound to the addresses as values. Performing a lookup in JS-QL happens by first looking into the lexical scope.

When variables with the same name are defined in both a function and the global scope, the lookup value of that variable will depend on the state that is currently matched. Therefore, we need to provide some sort of mechanism to 'overwrite' this default behavior, in case the address of the global variable is needed when the currently matched state is inside a function application. JS-QL recognizes the `_global` string as an indicator to perform a lookup in the global scope. Example 18 shows how variables can be looked up.

Example 18. The code in listing 4.9 demonstrates how variables are looked up in either the lexical scope or the global scope. First, the name of the right-hand side node of the assignment expression gets bound to `?rn`. When the assignment expression gets matched with a state in the global scope, all three address variables `?rnAddr`, `?globrnAddr` and `?xAddr` will have the same value. However, when the assignment on line 7 gets matched, `?globrnAddr` will point to the globally defined `x`, whereas the other two lookups contain the address of the locally defined `x`.

```

1  //Javascript program
2  var x, y;
3  x = {};
4  y = x;
5  var f = function(){
6    var x = 4; //local x gets declared
7    y = x;
8  }
9  f();
10 //JS-QL query
11 G.skipZeroOrMore()
12 .state({node:{
13     expression:{
14         type:'AssignmentExpression', right: {name:'?rn'}
15     }},
16     lookup:{
17         '?rn'           : '?rnAddr',      //lookup by variablename
18         '_global.?rn'   : '?globrnAddr', //lookup in global scope
19         'x'             : '?xAddr'       //lookup based on name
20     }}})

```

Listing 4.9: Looking up addresses in JS-QL

Limitations

A feature of the abstract state graph that affects the expressiveness of our language is that it displays states as they are evaluated. This means that for assignments for example, the address of the left-hand side of the assignment often isn't available

in the assignment state, as the value (and address) of the right-hand side needs to be evaluated first. This happens *after* the assignment state in the state graph. Example 19 illustrates this.

Example 19. Consider the following program: `var x, y; x = {}; y = x;` In this program, `x` gets assigned a fresh object, after which it gets aliased to `y`. `x` and `y` point to the same set of addresses after execution of this part of the program. The relevant graph part is depicted in figure 4.2

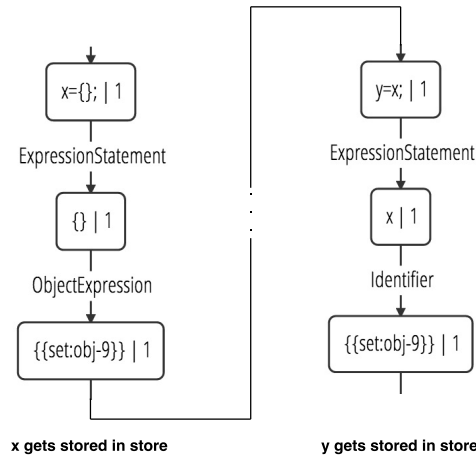


Figure 4.2: Assignment representation in the state graph

The problem with this kind of representation in the graph is that when we try to match the assignment in a query, no address information for `x` is available. After evaluating the fresh object, `x` gets stored in the store. Later on in the program, `y` gets assigned the value of `x`. Now, there is no problem because the address of `x` is already available in the store, so it can be looked up in the query. Note that the data flow detection in JS-QL is not as powerful as for example in a taint analysis. Queryies and policies can be written to mimic a taint-analysis, but this requires some work. Later in this chapter we will discuss how custom queries and policies can be defined.

4.1.9 Negation

Expressing which statements and expressions we want to detect on a path in the graph is made easy by JS-QL. Sometimes however, this does not suffice for some queries. For example, in some languages, accessing a file after it was closed results in an error in the application. This might compromise the integrity of the system. A naive approach to writing a policy for this would be to detect all calls to the `access` method that follow, after some wildcard states, the call of a `close`

method for a file f . While this query would match and return all violations against the policy, false positives would occur. This is because of the wildcard states between the two function calls. One of these calls could be a call to the `open` method, meaning that accessing the file afterwards is permitted.

Not: the language construct for negation

A better approach would be to specify that we do *not* want to encounter a call to `open` for f between closing and accessing it. This is exactly what the JS-QL `not` language construct does. When placing this construct right before a state, the query will only be matched if the negated state can not be matched with the current state in the state graph. When placing `not` before a state, and `star` or `plus` right after that state, it can be read as: "Match zero/one or more states that are *not* the negated state". A better query for the example above would then be written as in listing A.1, which can be found in the appendix for brevity reasons. The query first skips several states until it reaches a call to `close` on file f . The address of the file to be closed is also stored in a variable to correctly detect only the accessing and opening of that specific file. Next, all states are matched that are not opening f . Finally, the actual violation is detected, namely accessing the file after it has been closed and not re-opened.

Limitations

Negation is in the current version of JS-QL subject to some limitations:

1. Variables that are bound in a negated state, are only visible to that state. They will thus not be included in the resulting substitutions.
2. Currently, only one state can be negated. Negating sequences of states wrapped in braces is not yet supported. We plan to resolve this in the future.

4.2 Types of queries

The most straightforward way to query for properties is by just specifying a pattern and an input program. The pattern is then checked and each violating path is reported in the results. Sometimes however other types of queries are needed for the detection of specific policy violations. In this section we discuss the different types of queries and how they can be used.

4.2.1 Existential queries

Existential queries match a pattern *if there exists a path* in the state graph matching the query. All queries presented so far are existential queries. They report a violation of a policy for each path on which they encounter the violation. Existential queries can be defined as follows:

Definition 7. Existential queries: *Given an edge-labeled directed graph G where labels may have parameters, a vertex v_0 in G , and a parametric regular-expression pattern P , compute all pairs of vertex v in G and a substitution θ for parameters in P such that there exists a path from v_0 to v in G that matches some sentence accepted by P under θ .*

A consequence of definition 7 is that *any* path in the state graph matching user-defined query will produce a resulting substitution. For that path, the policy has been violated, but chances are that that path never gets executed when actually running the program, as a consequence of the overapproximations of the static analysis in JIPDA. A branch of a conditional might never be executed in a program for example. If the value of the test in the conditional gets overapproximated (i.e. with an abstract value of $\{Bool\}$), the state graph will depict both branches, as it can't decide which branch will be taken.

4.2.2 Universal queries

Universal queries provide stronger guarantees than existential queries, as they require that the query matches for the same substitutions along all possible paths in the state graph between two states. We define universal queries as follows:

Definition 8. Universal queries: *Given an edge-labeled directed graph G where labels may have parameters, a vertex v_0 in G , and a parametric regular-expression pattern P , compute all pairs of vertex v in G and substitution θ for parameters in P such that every path from v_0 to v in G matches some sentence accepted by P under θ .*

The intrinsic difference between universal and existential queries is how they match a pattern. Where it suffices for existential queries that just one path exists in the state graph, universal queries make sure that *all* paths between two points in the graph match the specified query. Example 20 shows an universal query:

Example 20. Imagine a JS-QL predicate `def ({name: '?x'})`, which checks all definitions and redefinitions of a variable bound to `?x`. This variable has a constant value in the state graph as long as no redefinitions of `?x` happens along any path between two states in the graph. We can then query for each state in

the graph where $?x$ has a constant value. The query in listing 4.10 shows how this can be expressed in JS-QL. Creating such predicates will be discussed in the next section. The definition of a variable v is matched, and any state following that matched state that isn't a redefinition of v will be contained in the result. All states in the state graph up until a redefinition of v (or the end of the graph) will then be contained in the resulting substitution set.

```

1 G.skipZeroOrMore()
2 .def({name: '?x'}) // Define the variable
3 .not().def({name: '?x'}).star // As long as it isn't redefined

```

Listing 4.10: Checking for constant folding using a universal query

4.2.3 Query direction

In most traditional systems, queries are viewed as straightforward, in the sense that they match a part of a graph or other program representation from point a to b . This way of reasoning implies that queries are always matched from the beginning to the end of a program (if control-flow information is available).

Our tool supports this manner of querying in the traditional way, but also allows to explore the state graph bottom-up. This can be meaningful to search for certain program properties. Queries can explore the state graph in two ways:

1. *Forward* queries are queries as we have defined them until now. They match the state graph from the beginning state to the final states of the state graph and are pretty easy to understand and read.
2. *Backward* queries on the other hand traverse the graph in a bottom-up manner, meaning that the query starts at the end of the state graph and matches states until the starting state of the graph is reached.

Although backward queries are less common, they can be useful to perform some program analyses, such as live variables analysis. This analysis calculates for each program point the variables that may be potentially read before their next write. A variable is thus live if it holds a value that may be needed in the future. Example 21 shows the backward query to perform a live analysis in JS-QL.

Example 21. The `use` and `def` predicates in listing 4.11 are again user-defined predicates. Starting from the resultstate of the program, some states are skipped until the first use of variable $?x$ is found. Note that this is in fact the *last* use of that variable in the state graph for that liveness set. The query then marks all states that aren't a write to $?x$. In this way, one or more states will be marked, representing the path on which variable $?x$ was live.

```

1 G.skipZeroOrMore()
2 .use({name: '?x'}) // Read the variable
3 .not().def({name: '?x'}).star // As long as it isn't written

```

Listing 4.11: Live variables analysis in JS-QL

4.3 Defining predicates and policies

Expressing vulnerabilities with only the `state` and `wildcard` constructs quickly becomes tiresome as every attribute of the state has to be explicitly specified. Our tool remedies this by letting users specify their own predicates and policies as well by providing some basic customizable predicates for single expressions and statements. We can distinguish predicates and policies by what they match.

1. *Predicates* are like the `state` construct, in the sense that they match only one specific state. For example, JS-QL has a built-in predicate `functionCall` which matches function calls. Predicates are useful in the sense that a user can specify what he wants to match in a state.
2. *Policies* on the other hand are sequences of predicates and/or `states`, forming a query pattern.

4.3.1 Creating a predicate

This section demonstrates how to write predicates by dissecting a relatively simple built-in predicate called `assign`. The full code for the predicate is listed in listing A.2 in the appendix.

Signature of a predicate

All predicates and policies can be written in a separate file, as long as they are extend in the *JSQL prototype*:

```
JSQL.prototype.assign = function(obj){...}
```

This is the basic notation for named predicates, in this case the `assign` predicate. The dots in the code above will be filled in by the actual predicate code. The `obj` argument represents the map of all properties of the state that need to be matched. The user is free in which properties and attributes he wishes to match or omit for a specific query, as discussed in the next section.

Specifying what a predicate has to match

The usefulness of predicates would drastically be reduced if the user has to again pass a nested map of properties to the predicate. We therefore let the developer of the predicate decide which properties he wishes to match, and how he names these properties in the predicate. We illustrate this in example 22.

Example 22. For the `assign` predicate, 3 basic attributes can be specified in the `obj` argument: `this`, `left` and `right`, representing the whole assignment node, its left- and right-hand side resp. In the definition of the predicate, a user can specify this as in listing 4.12.

```
1 var s = {}; // variable representing the state
2 var objThis = this.getTmpIfUndefined(obj.this); //optional
3 var objLeft = this.getTmpIfUndefined(obj.left); //optional
4 var objRight = this.getTmpIfUndefined(obj.right); //optional
5 //The following would make the right attribute mandatory
6 var objRight = obj.right; //mandatory
```

Listing 4.12: State properties of the `assign` predicate

Variable `s` will contain all information that we wish to match against a state in the state graph. When accessing a key in the `obj` map (like `obj.left`), the corresponding value is returned when found. When no such key exists, JavaScript returns `undefined`. To ease the use of predicates, some attributes in the `obj` map can be made optional. This is done by using the `getTmpIfUndefined` method, which returns a *temporary variable* when the value for its argument is `undefined`, and the regular value (a literal or a variable) when it is contained in the map.

Temporary variables

Temporary variables are variables that won't be contained in the resulting substitutions. By introducing these variables in the code, no conditionals have to be written that check whether an attribute has been specified in the `obj` map when a predicate is used, as we can just use a temporary variable as a replacement. In this way, a predicate also provides information that can be queried optionally.

Mapping attributes to the state graph

The *state chain* of a pattern state represents all information that has to be matched against the state graph. The state chain can be set up by mapping the attributes of the `obj` to a state in the state graph. To make things not too complicated for query and predicate developers, we provide a `setupStateChain` method which does just that. The `s` variable from example 22 will be used to build the pattern state

corresponding to a state the state graph. For each attribute that we provide through the predicate, an entry has to be made in `s`. This is illustrated in example 23.

Example 23. As seen in listing 4.13, `setupStateChain` takes three arguments:

1. The first argument represents the pattern state that is set up throughout the predicate. `setupStateChain` will add one attribute to the pattern state, depending on its second argument.
2. The second argument specifies the nested map that needs to be matched in the state graph. This argument is an array of keys that has to be read from left to right. Each entry goes one level deeper in the nested map, starting from the first entry of the array, which is a JS-QL keyword. The last entry of the array is the key whose corresponding value will be matched with the third argument of `setupStateChain`.
3. The third argument represents the literal or variable that needs to be matched against the last element of the second argument. This argument corresponds with either a variable previously defined, as in example 22, or a literal, as can be seen on line 4 of the example code.

Note that `setupStateChain` is not limited to querying the `node` property of a state. All information in the state graph can be queried through a predicate.

```
1 this.setupStateChain(s, ['node', 'this'], objThis);
2 this.setupStateChain(s, ['node', 'expression', 'left'], objLeft);
3 this.setupStateChain(s, ['node', 'expression', 'right'], objRight);
4 this.setupStateChain(s, ['node', 'expression', 'operator'], '=');
```

Listing 4.13: State chain setup of the `assign` predicate

Additional predicate information

JS-QL allows to specify properties, filters and lookups for predicates in the same way as for states. Putting everything together happens by finalizing each predicate state (only `s` in this case) and specifying the state(s) that match the predicate/policy. Example 24 shows how finalization is done and how the pattern is specified.

Finalizing handles lookups, filters and properties through the `finalize` method. This method extracts all relevant information from the `obj` map and adds it to the pattern state, which it receives as a first argument. Finally, the full predicate or policy pattern is specified and each state in the pattern or pattern gets initialized with its own designated pattern state. For predicates, there will always be at most

one pattern state. Policies however can have multiple pattern states, as they represent a sequence of states, each with their own pattern state. This is the only characteristic in which predicates and policies differ. An example of a policy can be seen in listing A.4 in the appendix.

Example 24. Defining a predicate always ends with the finalization of the pattern state. When finalized, the state map is passed to the `state` language construct, containing all information that has to be queried by the predicate.

```

1 this.finalize(s, obj); //Finalize a specific state
2 return this.state(s); //Fill in pattern state s

```

Listing 4.14: Finalizing the `assign` predicate

We can now use this predicate in any query, with the arguments that we wish to match in a state, as seen in Listing 4.15:

```

1 G.skipZeroOrMore().assign({left: '?l', right: '?r'})
2 G.skipZeroOrMore().assign({right: '?r', this: '?t', left: '?l'})
3 G.skipZeroOrMore().assign({left: '?l', right: '?r',
4                               properties:{
5                                   '?rName' : '?r.name'
6                               },
7                               lookup:{
8                                   '?rName' : '?rAddr'
9                               }}})
10 //...

```

Listing 4.15: Using the `assign` predicate

4.3.2 Recursion

Recursive queries are queries that can invoke themselves again, until a base case is matched. This type of query can for example be used to detect by which variables a variable is tainted (i.e. influenced/marked). JS-QL supports recursive queries by providing the `rec` function. This function takes two arguments:

1. The first argument represents the mapping for the next recursive step.
2. The second argument is the policy or predicate that has to be called recursively.

The `taintedBy` policy is included in the appendix as listing A.3. It describes a naive taint analysis which only considers simple assignments. It takes three arguments, which can all be omitted: `orig` denotes the original value which will

be aliased, `alias` represents the alias of the original value and `rec` keeps track of all variables that have been used as aliases inbetween `orig` and `alias`. The relevant code of the policy is found in example 25:

Example 25. The policy matches all simple assignments by name. Lines 1-8 set up the state maps of 2 separate states. The first state matches a direct assignment from `orig` to `alias`. The second state does the same, but the alias in this case is an intermediate assigned variable `flow`. When `a` is assigned to `b` and `b` to `c`, the resulting state looks like: `{orig: a, flow: b, alias: c}`, indicating that `c` is an alias of `a`, and that it obtained the value of `a` through `b`. Lines 10-16 show the pattern that needs to be matched.

We either match an assignment directly (the base case), or we match a state from `orig` to `flow`, and later in the graph from `flow` to `alias`. The recursive call will keep occurring until no more match is found in the state graph, or when the base case is matched. This policy shows that recursive queries can also be used to discover data flow properties of a program.

```

1  this.setupStateChain(s1, //State map s1
2                        ['node', 'expression', 'right', 'name'], orig);
3  this.setupStateChain(s1, //State map s1
4                        ['node', 'expression', 'left', 'name'], alias);
5  this.setupStateChain(s2, //State map s2
6                        ['node', 'expression', 'right', 'name'], orig);
7  this.setupStateChain(s2, //State map s2
8                        ['node', 'expression', 'left', 'name'], flow);
9
10 return this .lBrace()
11             .state(s1)                //1. From orig to alias
12             .or()
13             .state(s2)                //2. From orig to flow
14             .skipZeroOrMore()         // Skip some states
15             .rec(newObj, this.taintedBy) // From flow to alias
16             .rBrace();
17
18 //JS-QL query:
19 G.skipZeroOrMore({orig: '?o', alias: '?alias', rec: '?r'})

```

Listing 4.16: Recursive call of the `taintedBy` policy

4.4 Conclusion

In this chapter we presented the JS-QL language. We described the syntax and semantics of its language constructs. We first explained how the basic state construct can be used to match the state graph. Wildcards in JS-QL enable users to

specify that some states in the state graph can be skipped. Next, we described how to express disjunction in queries to allow for multiple matching paths in a single query. Additional properties and filters can also be specified in JS-QL, as well as the lookup of addresses and values of variables and functions. Finally, the JS-QL language construct for negation enables to specify the negation of basic states. This can be used to ensure that a state does not occur on the matched path.

We described the two types of queries that JS-QL supports. Existential queries match a pattern if at least one path is found, whereas universal queries require that the query matches for the same substitutions along all possible paths in the state graph between two states. Both types of queries can be used to explore the state graph. This exploration can be done traditionally by using forward queries, or by using backward queries to detect other program properties.

Finally, we discussed the difference between predicates and policies, and described how users can create them. Recursion in predicates and policies is also supported by JS-QL, as these kind of queries are useful for certain program analysis queries.

Chapter 5

Implementation

This chapter describes the implementation of the JS-QL tool and language, presented in chapter 4. The implementation of JS-QL is publicly available¹ and can be used freely to test source code for general characteristics and security vulnerabilities.

5.1 Architecture

The architecture of the implementation separates each component in a different module, providing the possibility to replace these modules by alternative implementations. In this section we discuss what each component represents.

Datastructures

The `DataStructures` module defines all datastructures used in JS-QL. These include all kinds of tuples used for the matching algorithm of our tool, but also the alternative representations of edges and nodes to transform the abstract state graph into a compatible graph for the matching engine.

AbstractQuery

The `AbstractQuery` module defines the core of the matching engine. It contains all operations on substitution sets: matching, merging, defining extra properties, filters and lookups. The module provides an interface to the query algorithms `ExistentialQuery` and `UniversalQuery` (see section 4.2), which perform the actual query matching processes.

¹<https://github.com/voluminat0/Jipda-Security>

Automaton

The `Automaton` module defines the uniform representation of finite state machines (also known as finite automata). It abstracts away whether the automaton is deterministic or non-deterministic, and provides information about the accepting, starting and intermediary states of these automata.

ThompsonConstruction

The `ThompsonConstruction` module defines an algorithm to convert a regular expression to a NFA (non-deterministic finite automaton). It parses the regular path expression and adds required states to the newly created automaton for each step in the parsing process.

SubsetConstruction

The `SubsetConstruction` module defines an algorithm to convert a NFA to a DFA (deterministic finite automaton). It eliminates all ϵ -transitions, which are transitions that can occur without reading an input symbol. The resulting automaton is used by both query algorithms.

JipdaInfo

The `JipdaInfo` module transforms state information to a more readable format for users. This transformation is necessary to enforce consistent datastructures for states containing information about an AST node. The transformed states are the actual states that are queried instead of the original JIPDA states.

JSQL

The `JSQL` module defines the internals of the JS-QL query language. It is implemented as an embedded DSL in JavaScript and allows users to define application-specific predicates and policies. The module is made available for the user through a fluent interface, increasing the readability of the language.

SecurityAnalysis

The `SecurityAnalysis` module glues together every component in the tool. This module invokes the initialization and transformation of the abstract state graph, as well as the execution of queries and the processing of query results.

5.2 User interface

The JIPDA analysis comes with an interface which enables the user to inspect the abstract state graph. This state graph is generated by performing abstract interpretation, provided that the user provides an input program and a lattice. For our tool we augmented this user interface in several ways described in this section. Figure 5.1 shows the user interface. A user can specify a JavaScript program and JS-QL query in the left column of the user interface. The middle column of the interface shows the actual state graph, together with a textual representation of the results. Finally, the right column gives a more detailed report of the query results. These results can be inspected by the user, as they are represented as JavaScript objects.

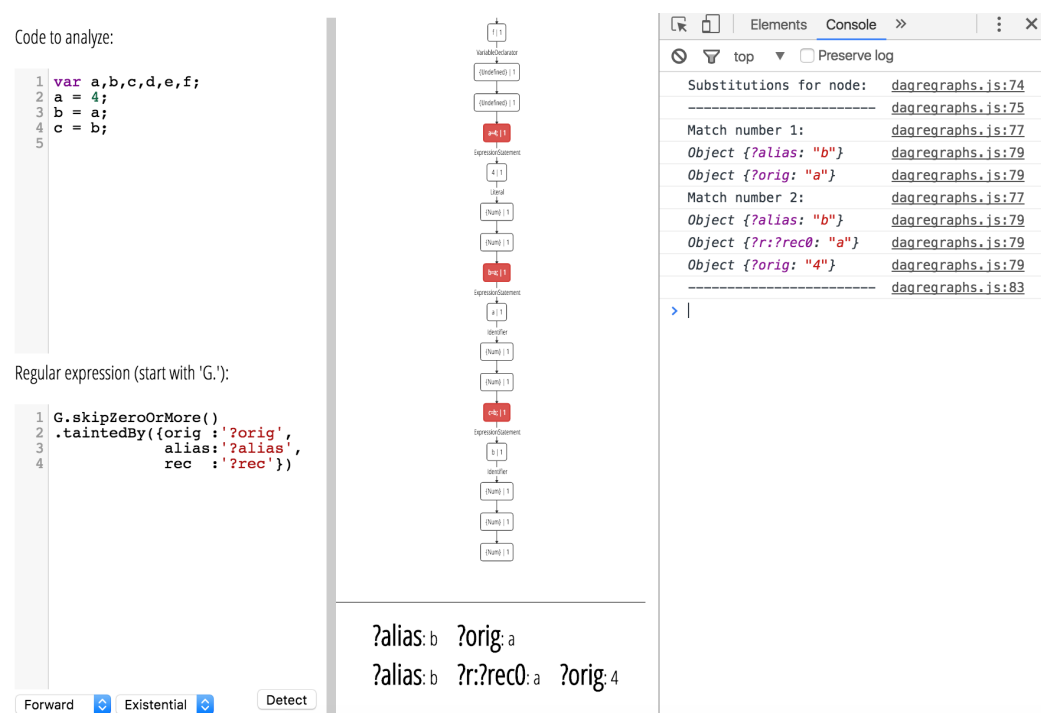


Figure 5.1: The JS-QL tool user interface

Query interpretation

Our tool enables the user to specify queries in the user interface itself. This way we avoid to switch between different screens and/or files to run just one query. The user interface contains a third-party JavaScript plugin which enables syntax

highlighting. The plugin is used for the input textboxes for a query and the input program. Along with entering the needed information, a user can decide the kind of query that needs to be executed. This can be done by selecting the direction (forward or backward) together with type of query (existential or universal). When pressing the 'detect' button, internally a new `Query` object is made with the provided query string. Query objects contain three fields: The query direction, its type and a `JSQL` object, representing the instantiated query. The query string is then converted to a `JSQL` object by evaluating it.

Abstract state graph

JIPDA already provides the functionality to display the abstract state graph in the user interface. We modified the representation of the graph so that it became optimal for the user to reason about query results:

1. *Edge labels*: As our approach uses edge labels to match states, we shifted information from nodes to edges. The JIPDA state graph already contains edge labels, but the information they contain is irrelevant for our approach. All evaluation states' outgoing edges are also augmented with a visible edge label representing the type of AST node it contains, to make it easier for the user to determine what to specify in his queries.
2. *State colours*: The default colours of all JIPDA states have been stripped from the graph. This was done to increase the contrast with marked states (i.e. states indicating a match of the query). When the matching engine produces all results, these results are transferred to the corresponding states of the state graph. A 'marker' property was added to each matched state, containing the match information as well as a CSS class to highlight them in the otherwise colourless graph. This CSS class can be customised by the user.

Results inspection

A query result is a set of substitutions, mapping variables (denoted by a starting `?`) to their corresponding values in the state graph. Every matching state is marked with its substitution set(s). These results can then be further explored in the results section under the state graph or in the browser's built-in console, which allows inspection of results in even greater detail.

5.3 The query language

The JS-QL query language is implemented as an embedded DSL with JavaScript as its host language. We motivated the use of a DSL in chapter 3 and explored the JS-QL syntax and semantics in chapter 4. This section describes how the DSL is implemented and how we incorporate several DSL implementation techniques. An overview of how queries are processed is depicted in figure 5.2.

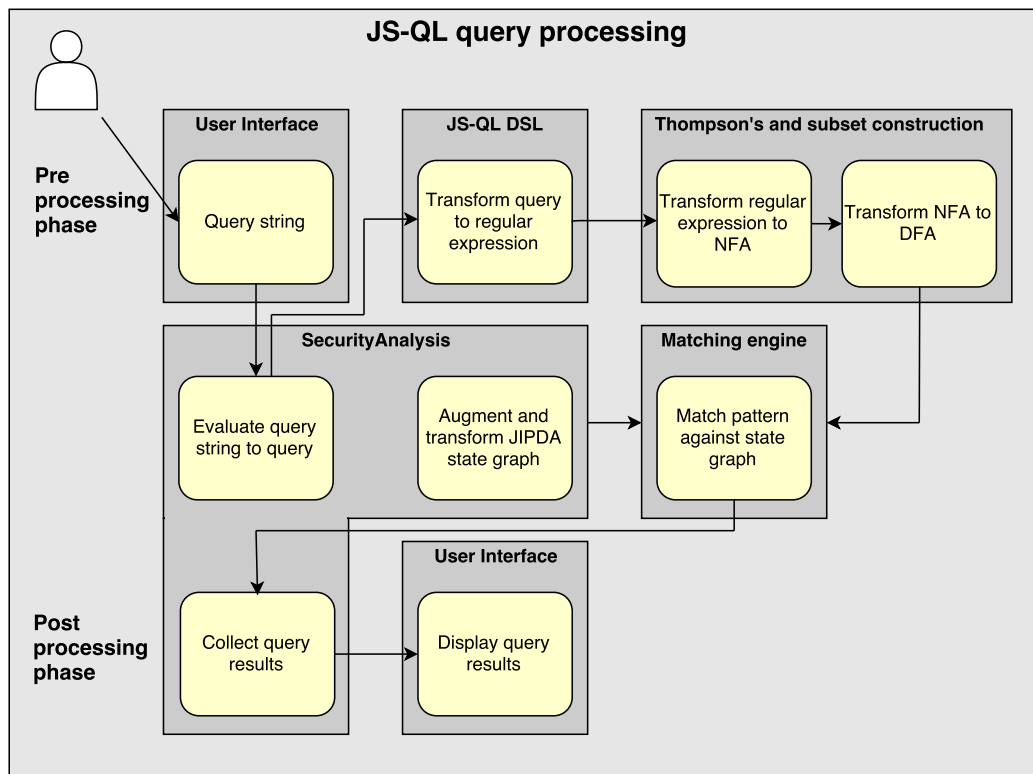


Figure 5.2: Stages of processing a query

Internal representation of pattern states

A JS-QL query is parsed like a regular expression. Each state in the pattern represents one character in the regular expression, defined by objects of type `RegexPart`. These parts of the pattern have 5 fields to ease the translation from regular expression to automaton:

1. *Name*: The name of a regular expression part. In the current implementation, the name denotes the type of the state/predicate that the `RegexPart` represents (e.g. `state`, `wildcard`, `not`, `lbrace`, ...)

2. *Symbol*: The actual symbol that will be parsed by the parser to set up the automaton corresponding to the query.
3. *Object*: The argument of the state/predicate in which all variables are bound and properties, filters and lookups are specified.
4. *ExpandFunction*: A higher-order function representing a recursive predicate or policy that is called for recursive queries. This argument does not need to be specified when a query is not recursive.
5. *ExpandContext*: A unique identifier to avoid overlapping recursive variable names. Only used for recursive queries.

States and predicates are function calls returning `this` to enable method chaining (which is a commonly used technique to implement a fluent interface). Each function call represents one state in the pattern, and thus for each of these calls the corresponding `RegexPart` gets pushed into a map containing the pattern information.

Handling recursion

Recursive query patterns can contain an arbitrary number of states, so they cannot be modelled directly as a sequence of `RegexParts` as the length of the actually matched pattern is not known. We therefore store a whole recursive query in just one `RegexPart` object, and mark it with 'subgraph' as its name. Additionally, we specify the `ExpandFunction` and `-Context` to be able to process the subgraph in the matching algorithm. The idea to treat recursive queries like this was adopted from the PQL language[27].

Transforming a query to an automaton

The entire query pattern (i.e. the map) is processed by applying *Thompson's Construction Algorithm* and the *Subset Construction Algorithm* consecutively to obtain a NFA and DFA respectively [36]. These algorithms won't be discussed in too much detail, as they are well described in many online resources and in the literature.

Regular, temporary and recursive variables

JS-QL supports three types of variables: Regular, temporary and recursive variables. Each of these types of variables play a particular role in the tool:

1. *Regular variables* contain the information that the user wants to match in a query. When a match succeeds, they are contained in the resulting substitutions.
2. *Recursive variables* are used as intermediary variables. They function as a variable that was bound in the previous step of a recursive query, enabling a recursive step to work with the value of one or more variables of the previous step. The `taintedBy` example from chapter 4 uses a recursive variable to store all intermediary assignments.
3. *Temporary variables* are state-local variables used when a user does not specify a certain argument for a predicate or policy. When only specifying the `left` argument for the `assign` predicate (See the example in chapter 4), the `right` and `this` attributes will be bound to temporary variables. These variables are dropped from the resulting substitutions.

By allowing the user to choose from three types of variables, writing queries becomes flexible because the bindings in a substitution set can be limited to only the information needed by the user. When imagining JS-QL without the support of temporary variables for example, the size of the substitution set for more complex queries would quickly grow large. This decreases the readability of the results and makes interpretation of these results much harder.

Deferring evaluation of properties and filters

One way to define properties is to use the `prop` function, and filters can be expressed through the `cond` function. Both of these functions have in common that the value they return depends on the value of the variables specified by the user. The problem now is that the value of these variables is not yet calculated at compile-time, and that the `prop` and `cond` functions thus can not use these values. Consider example 26:

Example 26. Imagine the following filter in a JS-QL query:

```
cond('==', '?var', 3)
```

Here, the state declaring `?var` is not yet matched in the state graph, meaning that `?var` is not yet bound and that we can not check if it is equal to 3. We remedy this by deferring the evaluation of the specified function. Instead of passing the result of evaluating the function directly with its arguments, we wrap them into a *thunk* and pass that *thunk* to the matching engine. When the matching engine finally needs the value of the *thunk*, it unwraps it and resolves all variables to the values to which they are bound. If not all variables are bound, the query fails.

5.4 Matching engine

The algorithms for existential and universal queries that are used as the base of the tool were first presented by Liu et al [26]. They discuss algorithms for matching regular path expressions with graphs containing simple information. These algorithms match the edge labels of the graph with the edge labels of the regular path expression (in the remainder of this dissertation, we will call these expressions *patterns*). For our implementation, this presents 3 obstacles:

1. *Subgraphs*: Recursion can be a useful tool for certain analyses based on queries. The algorithms presented by Liu et al. do not support recursion, and thus do not provide constructs for recursive queries. We augmented these algorithms to consider subgraphs as a regular data structure and implemented a way to process them.
2. *Information in edge labels*: The JIPDA state graph can be considered as a sort of linked list of states. Each state contains information about itself but also has references to its successor states. Although this being only a minor obstacle, we had to find a way to transform the JIPDA state graph in such a way that all state information was available in the edges, instead of in the states. As no explicit edge information was available in the JIPDA state graph, we introduced a new type of graph representation containing tuples with a source state, an edge label (containing the source state information) and a target state. This graph representation is better suited to be processed by the aforementioned algorithms.
3. *Edge label information*: The information on the edge labels in the approach described by Liu et al. consists of simple information. The arguments of a pattern can only be symbols, like a string or a literal, limiting the type of graphs that can be analysed. We remedy this by extending the algorithms to support nested maps as arguments, as these are the main datastructure in JS-QL for representing a state.

In the remainder of this section we discuss the core functionality of the matching engine. In section 5.4.1 we briefly discuss the inputs and outputs of the matching engine. We then elaborate on the algorithms for solving existential and universal queries in section 5.4.2. All functionality used by these algorithms is discussed in sections 5.4.3, 5.4.4 and 5.4.5. The flow of both algorithms is quite similar, and is depicted in figure 5.3.

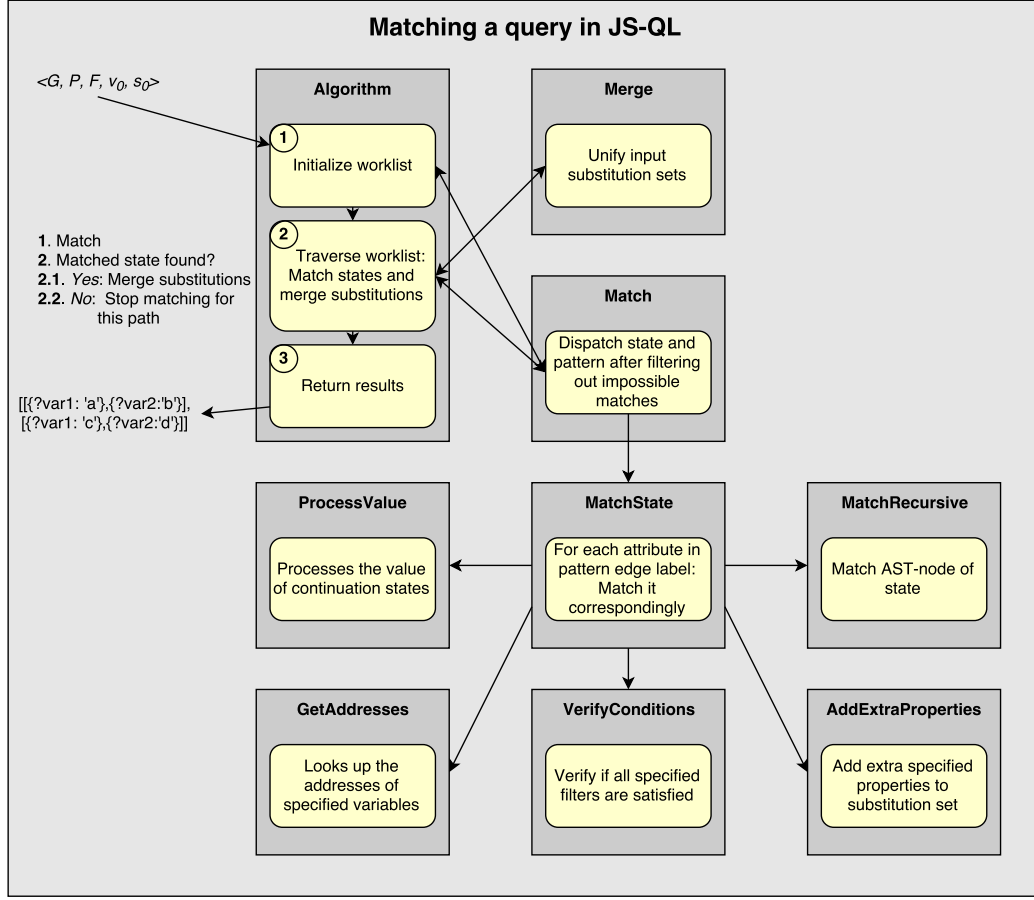


Figure 5.3: Stages of matching a query

5.4.1 Inputs and output

The inputs for both the existential query algorithm as the universal query algorithm are identical. In order to match the state graph with a pattern, we have to provide both the graph and the pattern to the algorithm. The generated automaton for the pattern P as well as the state graph G are transformed to a uniform format, called `triples`. A triple in a pattern consists of two automaton states as source and target state and the edge between them, representing the part of state that needs to be matched (i.e. the nested map of state information). For the JIPDA state graph we transformed the original graph to a similar representation, as already described above. The final states F of P also need to be specified, so that the algorithm can determine when a match is completed and its substitutions can be added to the resultset. Finally the initial states of both the automaton (s_0) and the state graph (v_0) are also required, giving the algorithm an indication on where it should start matching. Together, this information forms the 5-tuple

$\langle G, P, F, v_0, s_0 \rangle$.

The results of the algorithm consists vertex-theta pairs, where a vertex is a state in the abstract state graph and theta is the set of all possible substitutions for the query ending in that state. In our implementation, we call these pairs `VertexThetaPairs`, and they form the tuple $\langle v, \theta \rangle$.

5.4.2 Query algorithms

The semantics of both algorithms can be divided into two main phases. The first phase creates and initializes the worklist, while the second phase processes each element in the worklist and adds new elements to it as long as a pattern is matched. We describe both phases in this section for existential queries, and explain the differences with the algorithm for solving universal queries.

The worklist initialization phase

The first part consists of initializing the worklist. This worklist W contains triples of the form $\langle v, s, \theta \rangle$, where v is a state of the state graph, s a state of the automaton and θ_s the set of substitutions that have been matched up until s in the pattern. The algorithm loops over each state in the state graph to locate a triple t_G in G having the starting state v_0 as its source. Next, all triples in P are traversed until initial state s_0 is found as the source state of a triple t_P . When both triples are found their edge labels are *matched*. If the matching succeeds, a list of all possible substitutions θ is returned and the worklist gets updated to contain the destination states of t_G and t_P together with a substitution from θ . Producing a match from two edge labels is discussed in section 5.4.3. If no match between v_0 and s_0 is found, the query fails and no results are returned, as a match for the initial states can not be found anywhere in the state graph.

The worklist processing phase

In the second phase of the algorithm, worklist W gets traversed. W contains a state v of the state graph, a state s of the automaton and the partial match and substitution set θ between these two states. Each successor (v_{succ} and s_{succ}) of both v and s are tried as the next match in a pattern, unless s_{succ} is a state in the automaton representing a subgraph. If this is the case the pattern gets expanded, as is explained in section 5.4.5. When a match is found, each found substitution θ_{succ_i} between v_{succ} and s_{succ} is merged with θ . If this merge succeeds, the triple $\langle v_{succ}, s_{succ}, \theta_{succ_i} \rangle$ is added to W , only if it hasn't already been processed in an earlier matching step. This is called *fixpointing*, and is applied by keeping track of the already reached triples in the reach list R in order to prevent the algorithm

from looping forever. The merging process is described in more detail in section 5.4.4.

After acquiring the next triple(s) for the worklist for a certain v and s , the algorithm checks whether s is contained in the list of final states F . If it does, a `vertexThetaPair` is added to the resultlist containing v (the state of the graph matching the final state of the pattern) and θ (the set of all substitutions between v_0 and v). When the worklist is depleted, no more paths need to be matched, indicating that all possible results have been collected. All `VertexThetaPairs` are returned so that they can be processed in the user interface layer.

Differences with the algorithm for universal queries

The algorithm described in the previous section is used to solve existential queries. Universal queries use an algorithm which is very similar, except that it performs an extra check for the *determinism condition* in the second phase of the algorithm.

Definition 9. The *determinism condition* imposes that for each path from v_0 to v in G , all paths in P that match it (under any substitutions) pass through the same set of states.

We implement this condition by setting a flag when a match is found for one path in P . If a match is found for another path in P , the determinism condition is violated and the matching engine halts execution. In this case, no results will be produced. Another condition for universal queries to produce results is that for each matching state in G , the corresponding state in P should be a final state. This last condition is rather trivial, as queries only produce a result if they are matched up until a final state.

5.4.3 Matching states with a pattern

Matching in the strict sense of the word means checking if two things are equal. In our implementation, a match occurs when a state in P is *subsumed* by a state of G . What this means is that all the information that is contained in a state in the pattern has to occur in the state of the state graph that is currently being matched, allowing the latter to contain more information than only what is specified by the pattern state. Figure 5.4 illustrates how a state is matched. The JS-QL predicate on the right produces a match, as it is subsumed by the JIPDA state. In contrast, the left JS-QL predicate specifies a `callee` attribute, which is not contained in the JIPDA state. This suffices to produce a mismatch, leading to a failed match for the currently matched path in the state graph.

The JS-QL tool matches states using the `match` function. This function is an entry point to the matching process, as it only passes all matching work to

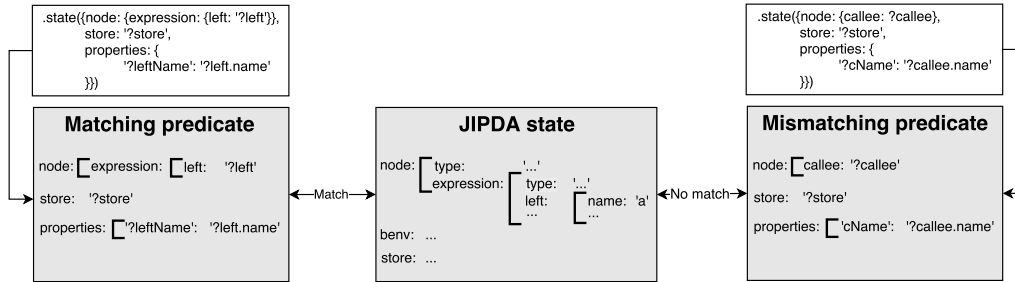


Figure 5.4: A matching and mismatching predicate for a JIPDA state

the `matchState` function and waits for its results. `match` however does perform an initial check to make sure no excessive work is done: when encountering a wildcard in the pattern, no matching needs to be done as a wildcard matches any state. Negation is also handled by this function: matching a negated pattern state consists of matching the regular state (i.e. the state without negation) and returning false when a match is found and the empty substitution list otherwise.

The remainder of this section discusses the different phases of the matching process as depicted in figure 5.3.

matchState

The `matchState` function is responsible for delegating the matching of keywords and combining the results of those matches. The initial substitution set θ is empty and grows larger for each keyword that is matched. Internally, the function works as follows: for each keyword specified in the JS-QL query, `matchState` matches its value (i.e. a nested map, a literal or a variable) with the corresponding attribute of the state to be matched and collect the results of this partial matching. If the partial match failed, `false` is returned, otherwise the partial match is merged with θ . Each possible keyword has a different processing method (see figure 5.3), and we briefly discuss each of them next.

matchRecursive

The `node` attribute of a state represents its corresponding AST node. This node is matched recursively until a variable or a literal is encountered. In the case of a variable, the corresponding AST node value is bound to it. If each node-attribute of the predicate is matched, the substitution set containing all matched variables is returned. There are several cases in which the `matchRecursive` function does not produce a match:

1. The AST node gets matched recursively until a variable or literal is encountered. In the case of a literal being matched, a mismatch occurs when the

value of the literal does not agree with the value in the AST node.

2. In the other case, matching a variable which was already bound in a previous state results in a mismatch if the value of the variable can not be unified with the newly matched value.
3. The most common reason for a mismatch is when a node-attribute specified in a JS-QL query is not present in the AST node of a JIPDA state. This 'mismatching-technique' is often used instead of explicitly specifying the *type* of the node in the predicate. Figure 5.4 illustrates this: The predicate on the right-hand side does not match as no 'callee' attribute is present in the current JIPDA state.

addExtraProperties

This function matches the properties attribute of a predicate. The matching process is split in two, using one function for each way in which properties can be defined: One function handles properties that access attributes of already bound variables. The other function handles properties specified by `prop`. Both functions first resolve all needed variables, and fail to match if one or more variables cannot be resolved (i.e. are not contained in the current substitution set). After resolving all used variables, the new variables defined by the properties are evaluated and added to the substitution set to be returned. `addExtraProperties` may produce no results if any of the same reasons discussed for `matchRecursive` occur.

verifyConditions

JS-QL allows to express filters, and `verifyConditions` is the function that evaluates these filters. Its internal working is similar to the matching of properties. After resolving the needed variables, the specified filter function is applied to its arguments. When the condition for a filter holds, the next filter is checked. In the case that a condition for a filter does not hold, the matching process is aborted. If all filters return `true`, the matching process can continue as the matched state meets all requirements that the filter imposes.

getAddresses

The `getAddresses` function looks up the addresses for the variable specified in the lookup map. Because of the precision loss due to abstract interpretation, variables can have multiple addresses. For each name in the map, a literal or a variable to be resolved, the addresses are looked up using the binding environment

and the store. When no address is found for the specified name (meaning that the variable does not exist at that point in the program), the matching process fails.

processValue

Continuation states have a 'value' attribute. This attribute contains the addresses or values for an expression or statement that has been evaluated. The `processValue` function duplicates the existing substitution set and adds one address/value to each of the duplicated substitution set. The resulting substitution sets each contain one possible value or address.

5.4.4 Merging substitution results

Merging happens when the substitution set of previously matched state in the pattern has to be combined with the newly acquired substitution set for the currently matched state. When these substitution sets can be combined, a valid next step in the state graph is found with the newly created substitution set θ_{res} . Else, the algorithm halts for the current path in the state graph, as the substitution sets can not be merged. Merging in our tool is fairly straightforward.

A merge between two substitution sets θ_i and θ_j only succeeds if no substitution of θ_i is contradicted by a substitution in θ_j , and vice versa. When one substitution set contains a substitution that is not contained in the other, the resulting substitution set will also contain that substitution. Two contradicting substitutions result in a mismatch, making the algorithm halt for the currently matched path. The merging process is illustrated in example 27.

Example 27. Table 5.1 shows the possible outcome θ_{res} of merging two substitution sets θ_i and θ_j .

	θ_i	θ_j	θ_{res}
1	?var1: x ?var2: y	?var3: x	?var1: x ?var2: y ?var3: x
2	?var1: x	?var1: y	false
3	?var1: x	?var1: x ?var2: y	?var1: x ?var2: y

Table 5.1: Examples of merging two substitution sets

The first entry in the table successfully merges the two sets because they are contain disjunct information. No overlaps in variables occur, so the resulting set is the union of both sets. A mismatch is encountered in the second entry. The

substitution value for `?var1` in θ_i differs from that in θ_j , resulting in a failed merge. The last entry again poses no problem to merge as `?var1` contains the same value in both sets and `?var2` is only contained in the second set.

5.4.5 Processing subgraphs

Recursive query calls in pattern P are represented by a single state of type 'subgraph'. When encountered in a query solver algorithm, this state has to be expanded in such a way that the pattern gets modified to contain *one* additional recursive step. The query solver algorithms used by JS-QL match a state of graph G with a state of P , and halts the matching process for that path when no match is found. This has as a side effect that we indeed do not have to try and exhaustively expand each subgraph state, because the algorithm might never reach the expanded states. Another consideration is that if we were to expand the subgraph state multiple times, the algorithm might get trapped in an infinite loop as it does not know when to stop exploring recursive steps.

Figure 5.5 shows what happens when a recursive state of the `taintedBy` policy is encountered by a solver algorithm. We see that the subgraph in the original policy gets replaced by the entire pattern of that policy in the first recursive step.

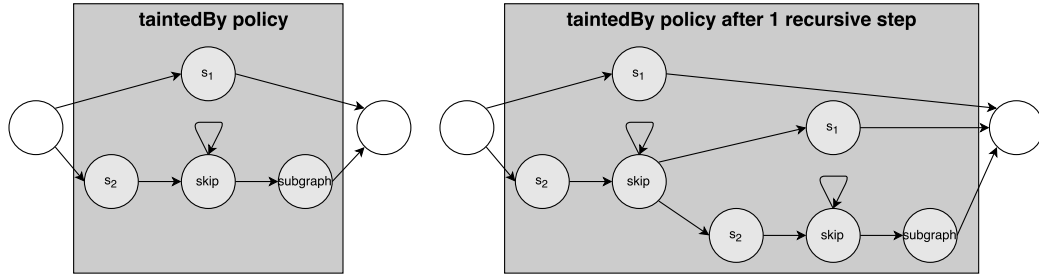


Figure 5.5: Before and after expanding a subgraph for one recursive step

Expansion of a subgraph state happens by applying the `expandFunction` (section 5.3), which is a predicate or policy returning a piece of a pattern $P_{subgraph}$, and replacing the subgraph state in P by the obtained pattern $P_{subgraph}$. The same subgraph may be expanded for different paths in the state graph, resulting in costly computations for each of those paths. We remedy this by caching each expanded subgraph. Each subgraph state (with its unique identifier) is mapped to its expanded subgraph pattern. When in the next iteration of the algorithm a subgraph state is encountered, its corresponding subgraph pattern is first looked up in the cache. Only when there is no corresponding subgraph available, the subgraph is calculated and added to the cache.

5.5 Conclusion

In this chapter we discussed the implementation of the JS-QL tool. As the code of our tool is logically subdivided in several functionality layers, we describe the architecture of the tool and discuss each component in it. We provide an overview of the user interface, and explain how it can be used and interpreted. Our tool uses the JS-QL query language to express queries, and we describe several implementation techniques used to build JS-QL. Finally, we also discuss the workings of the matching engine, which is the core of the tool. We explain how queries are matched and results are merged, and describe how results are accumulated.

Chapter 6

Evaluation

In this chapter we validate and evaluate the expressiveness of the JS-QL query language by expressing 9 security vulnerabilities distilled from 3 papers in sections 6.2, 6.1 and 6.3 respectively. Every vulnerability expressed in JS-QL will be evaluated by comparing how well it matches the vulnerability expressed in the original paper. Finally, in section 6.4, we evaluate the our tool by specifying its advantages and limitations. We will also briefly compare the query languages presented in this chapter in terms of expressiveness, verbosity and conciseness.

6.1 The GateKeeper language

In this section we express 3 vulnerabilities originally presented in GateKeeper. GateKeeper is a mostly static approach for soundly enforcing security and reliability policies for JavaScript programs [14]. Programs are represented as a database of Datalog rules, against which GateKeeper policies (also written in Datalog) are checked.

6.1.1 Writes to prototype objects

Many websites use bookmarklets to store user information to automate the login process, as for example discussed by Adida et al. [2]. This is a common strategy used to reduce the amount of information the user has to enter every time he visits the website. An attacker website however can alter the JavaScript environment in such a way that he can steal all of this information from the user. Imagine a simple login function which checks the current location of the webpage to verify that it is on the correct webpage. The current location can be compromised by overwriting the `toString` function of the `String` object, as depicted in listing 6.1. This function can be configured to always return a “good” location. In this way, the

login function can be called in the environment of a malicious website, possibly leaking sensitive information.

```

1 String.prototype.toString = function() {
2     //Always return "spoofed" url
3     return "www.goodwebsite.com";
4 }
5
6 var login = function() {
7     if(document.location.toString() === "www.goodwebsite.com") {
8         //leak information on untrusted website
9     }
10 }

```

Listing 6.1: Prototype poisoning example

GateKeeper policy

Gatekeeper expresses vulnerabilities by defining a set of rules in datalog. For example, in order to detect writes to prototypes of builtin objects, GateKeeper defines the `FrozenViolation(v)` predicate, shown in listing 6.2. This predicate first looks for all stores of field `v`. This field points to location `h2`, which represents the points-to address for variables. Only writes to builtin objects are infringements of the policy, which implies that `h2` has to point to a field of one of these objects. This is expressed as follows: in `BuiltInObjects(h)`, `h` points to the heap location of a builtin object. The `Reaches(h1, h2)` predicate makes sure that the field that was stored reaches the builtin object directly or indirectly, by recursively checking if one of the properties of the builtin object has a field pointing to the stored field.

```

1 Reaches(h1, h2) :- HeapPtsTo(h1, _, h2) .
2 Reaches(h1, h2) :- HeapPtsTo(h1, _, h3) ,
3                     Reaches(h3, h2) .
4
5 FrozenViolation(v) :- Store(v, _, _) ,
6                       PtsTo(v, h2) ,
7                       BuiltInObject(h1) ,
8                       Reaches(h1, h2) .
9
10 % Specify all built-in objects
11 BuiltInObject(h) :- GlobalSym("String", h) .
12 BuiltInObject(h) :- GlobalSym("Array", h) .
13 % ...
14
15 GlobalSym(m, h) :- PtsTo("global", g) ,
16                   HeapPtsTo(g, m, h) .

```

Listing 6.2: Policy 1 in GateKeeper

JS-QL policy

JS-QL also supports expressing similar queries. We augmented the JIPDA-nodes corresponding with `MemberExpressions` with two extra fields: `mainObjectName` and `properties`, representing the root object and the property-chain array that was accessed respectively. An example: for memberexpression `o.x.y.z`, `o` is the `mainObjectName`, and `[x, y, z]` is the array `properties` which represents the properties that are chained. Listing 6.3 depicts the JS-QL query to efficiently express this vulnerability. Note that the filter on lines 10-12 can be omitted. This filter indicates that we only want to detect writes to the `prototype` property of the `String` object. When this is omitted, we will detect all writes to this object.

```
1 G.skipZeroOrMore()
2 .state({
3   node:{
4     expression:{
5       left:{
6         properties: '?props',
7         mainObjectName: 'String'
8       }
9     }
10  },
11  filters:[
12    cond('contains', '?props', 'prototype')
13  ]
14 })
```

Listing 6.3: Policy 1 in JS-QL

This example JS-QL policy only detects writes to the `String` object. We wrote a compound policy `writeToBuiltinObjectPrototype` to detect writes to all builtin objects' `prototype` property. The code for this policy can be found in listing A.4 in the appendix. This policy is just the disjunction of states similar to the state in listing 6.3, with the only difference in the `mainObjectName` property, which corresponds to a different builtin object name.

Discussion

JS-QL proves to be able to express the prototype poisoning policy, as well as similar policies. The `GateKeeper` policy was more verbose compared to its JS-

QL equivalent, indicating that JS-QL policies can be concise while remaining expressive.

6.1.2 Global namespace pollution

Working in a JavaScript environment often involves the inclusion of multiple (third-party) scripts. These scripts offer access to functionality which would be tiresome to implement for every project yourself. Some of these scripts are written by other parties, so developers cannot be sure that these parties follow the same coding guidelines as they do. Inexperienced programmers might not be aware of the JavaScript namespacing patterns [30]. This leaves an open window for a phenomenon called “global namespace pollution”. Defining variables in the global scope in JavaScript can lead to unanticipated behaviour of the program when another script defines a global variable with the same name.

GateKeeper policy

Preventing stores to the global object (i.e. in the global scope) can be enforced with a two-line GateKeeper policy. GateKeeper handles the global object explicitly by defining a variable `global`. Global variables can then be simulated as fields of this object. A policy to detect global stores can then be defined as in listing 6.4: The global object variable is located on address `g`. Every field store `h` that points to a field of `g` will then be detected by the `GlobalStore` policy.

```

1 GlobalStore(h) :- PtsTo("global", g),
2                   HeapPtsTo(g, _, h) .

```

Listing 6.4: Policy 2 in GateKeeper

JS-QL policy

We could write a similar policy in JS-QL that would also verify whether the address of the variable points to the global object. However, this is more difficult in our system because of the flog graph generated by JIPDA. When a variable or function gets declared or when a variable is assigned to, the right-hand side first has to be evaluated. This is also reflected in the JIPDA graph. Only when the expression is evaluated, the store and environment are modified to contain the recently evaluated information. The allocation address for newly created variables is not yet available in the states we query on lines 3,5 and 7 in listing 6.5. We remedy this by looking further down the graph, more specifically in the states where this information *is* available.

The policy is implemented as follows: After skipping to an assignment or a declaration of a function or variable, we bind the name the variable's or function's name to metavariable `?name`. We then again skip some nodes until we find a state where the address of `?name` is available and bind it to `?nameAddr`. Finally, we search for the variable or function with the same name in the global object and also bind it to `?nameAddr`, which filters the resulting substitutions to only contain information about globally declared objects.

```
1 G.skipZeroOrMore()
2 .lBrace()
3   .assign({leftName: '?name' })
4   .or()
5   .variableDeclaration({leftName: '?name' })
6   .or()
7   .functionDeclaration({name: '?name' })
8 .rBrace()
9 .skipZeroOrMore()
10 .state({lookup:{
11     '?name' : '?nameAddr' ,
12     '_global.?name' : '?nameAddr'
13   }})
```

Listing 6.5: Policy 2 in JS-QL

Discussion

We conclude that JS-QL is capable of expressing a policy for detecting global namespace pollution, and that the resulting queries are more verbose and explicit than their equivalent in GateKeeper. This is because GateKeeper has a database of points-to analysis information available, whereas JS-QL has to specify a lookup manually.

6.1.3 Script inclusions

A well known exploit in JavaScript environments is *heap spraying* [6]. This is an attacking technique that can eventually even compromise a user's system. In short, heap spraying arranges the layout of the heap by allocating a vast amount of carefully-chosen strings, installing a certain sequence of bytes at a predetermined location in the memory of a target. When this is achieved, the exploit is triggered and a script is executed, possibly compromising the victims system. Such an aggressive attack can be instantiated on the victim's computer by simply including a malicious script. To prevent this, a developer can write a policy which detects all script inclusions. Regular script inclusions through `<script></script>` tags can be detected by hand. Javascript however also allows programmers to write

arbitrary HTML code by using the `document.write` function or similar functions (e.g. `document.writeln`). Listing 6.6 gives an example of malicious script inclusions.

```

1 var evilScript;
2 var scripts = ["<script>bad1</script>", "<script>bad2</script>"];
3
4 for(var i = 0; i < scripts.length; i++){
5     evilScript = scripts[i];
6     document.write(evilScript); //Script inclusion
7 }
8
9 var o = {};
10 o.f = document.writeln;
11 o.f("<script>bad3</script>"); //Script inclusion

```

Listing 6.6: Script inclusion example

GateKeeper policy

The policy for detecting script inclusions can be written with only a few lines of datalog in GateKeeper, as depicted in listing 6.7. What needs to be detected are the calls to `document.write` and similar methods, even when they are aliased. This is important because scripts containing attacks are often obfuscated. `DocumentWrite(i)` first looks for the address `d` on the heap which points to the global `document` object. Next, the location of the property `write/writeln` of that object is reified in variable `m`. This is also an address on the heap. The last step is to find all call sites `i` that point to that same address on the heap.

```

1 DocumentWrite(i) :- GlobalSym("document", d),
2                     HeapPtsTo(d, "write", m),
3                     Calls(i, m).
4
5 DocumentWrite(i) :- GlobalSym("document", d),
6                     HeapPtsTo(d, "writeln", m),
7                     Calls(i, m).

```

Listing 6.7: Policy 3 in GateKeeper

JS-QL policy

JS-QL can also express the policy listed in 6.7. The approach we take first skips zero or more states in the JIPDA graph. We specify that we then want to find a function call with the name of the function bound to metavariable `?name`. In order to know to which address the called function points in the store, we look it up and

bind the address to `?addr` in the lookup-clause of the `fCall` predicate. Finally we also match the address of `document.write/document.writeln` to the same `?addr` metavariable, filtering out all function calls that do not point to this address.

The analysis that we use is context-sensitive and Javascript is lexically scoped. This implies that we need to explicitly specify that we are looking for the address of the *global* `document.write` object. If we did not do this and the user has defined an object with the name “document” and a property “write” or “writeln” inside the scope of the current state in the graph, we would get the address of that object instead of the global object. `_global` is the JS-QL keyword indicating that we are looking up an address in the global namespace, as depicted in listing 6.8.

```
1 G.skipZeroOrMore()
2 .lBrace()
3 .fCall({
4   name: '?name',
5   lookup:{
6     '?name'      : '?addr',
7     '_global.document.write': '?addr',
8   }
9 })
10 .or()
11 .fCall({
12   name: '?name',
13   lookup:{
14     '?name'      : '?addr',
15     '_global.document.writeln': '?addr',
16   }
17 })
18 .rBrace()
```

Listing 6.8: Policy 3 in JS-QL

Discussion

Although the example demonstrates that the JS-QL query is more verbose than its GateKeeper counterpart, we conclude that we are able to express policies for detecting script inclusions.

6.1.4 Conclusion

In this section we expressed 3 security-related policies in the GateKeeper language and JS-QL. As table 6.1 indicates, all security vulnerabilities expressed in GateKeeper were also expressible in JS-QL. Gatekeeper excels in writing concise

policies to detect certain individual properties of a program. It is however difficult to express a policy which finds a sequence of properties in a program. JS-QL does not have this limitation. The language is designed to match states along an abstract state graph. While it can also express individual properties of a program such as calls of a certain method, it is also capable of finding complex patterns. Two other features that JS-QL offers and GateKeeper lacks is filtering and defining extra properties. It would be very cumbersome to write a policy in GateKeeper to find all function calls to methods that take more than four arguments, which can be considered as a code smell [38]. JS-QL provides the `properties` and `filters` constructs to express this.

Language	Policy 1	Policy 2	Policy 3
Gatekeeper	✓	✓	✓
JS-QL	✓	✓	✓

Legend: ✓: Fully expressible

Table 6.1: Expressiveness in JS-QL and GateKeeper

We argue that our language is more expressive since we are able to express sequences and extra properties/filters for example, increasing the flexibility of policies. GateKeeper on the other hand is less verbose in most situations. This is because we have to express everything we want to detect inside the constructs of JS-QL (like `state({ . . . })`). Data flow analysis happens behind the scenes in GateKeeper, whereas JS-QL has to do the checks for aliasing in the language itself. An example can be seen in 6.1.3, where we have to explicitly match the address of the called function to the address of `document.write`. This matching happens internally in Gatekeeper.

6.2 The PidginQL language

In this section we express 3 policies originally presented in Pidgin [22]. Pidgin presents a query language, PidginQL, that queries a program dependence graph. This type of graph is different from the flow graph generated by JIPDA because it only depicts dependencies between program statements, rather than modelling the whole execution of a program.

6.2.1 Only CMS administrators can send a message to all CMS users

In a scenario where not only administrators can broadcast messages, a regular user with bad intentions could easily take advantage of this situation to cause harm to the system. A CMS application for instance with a decent size of users could be exploited by sending a message to all users, asking them to provide with sensitive information, such as their password. When the attacker provides a reason to the victims convincing them to send their password, he could possibly compromise the contents of the victim's account. This behaviour is undesirable, thus we need a policy which prevents regular users from sending such messages.

Pidgin policy

The policy described in Pidgin that addresses this issue can be found in listing 6.9. First, all nodes that are entries of the `addNotice` method are searched for and stored in a variable. `addNotice` is the method that sends messages to all users. Next, all points in the PDG are found that match a return node of the `isCMSAdmin` method with a return value which is truthy. In order to know if there exists some path in the graph where `addNotice` is called when the return value of `isCMSAdmin` is false, all paths between the nodes in `addNotice` and `isAdmin` are removed from the graph for all paths where `isAdmin` is true. Finally, the intersection of the nodes in this 'unsanitized' graph and the nodes in the `sensitiveOps` argument, which represents a broadcast in this case, is taken. When this intersection is not empty, we can assume that there is a violation of the policy in the remainder of the graph. This last part is exactly what the `accessControlled` method does.

```
1 let accessControlled(G, checks, sensitiveOps) =
2   G.removeControlDeps(checks) ∩ sensitiveOps is empty
3
4 let addNotice = pgm.entriesOf("addNotice") in
5 let isAdmin   = pgm.returnsOf("isCMSAdmin") in
6 let isAdminTrue = pgm.findPCNodes(isAdmin, TRUE) in
7   pgm.accessControlled(isAdminTrue, addNotice)
```

Listing 6.9: Policy 4 in PidginQL

JS-QL policy

When attempting to write a similar query in JS-QL, we need to define the problem in terms of control flow: “There must be no path between the returns of `isCMSAdmin` when the return value is false, and a call of the `addNotice`

method.” With abstract interpretation, a value can be both true and false, which is why we have to inspect the nodes in the state graph. When looking at a conditional (like an `IfStatement`), we can determine whether the true or false branch has been taken by comparing the first node of the branches with the alternate/consequent of the conditional. This can be seen on lines 2 and 6 of listing 6.10, where the `?alt` variable of the `IfStatement` gets matched with one of the successive states, ensuring that that state is the beginning of the false branch. We bind the context of the branch state to `?kont` and the stack to `?lkont`. The next time we find a state with the same context and stack, we know that the end of the branch has been reached. Lines 8-9 indicate that we only wish to find the calls to `addNotice` before the end of the branch.

```

1 G.skipZeroOrMore()
2 .ifStatement({alt: '?alt'})
3 .skipZeroOrMore()
4 .fCall({name: 'isCMSAdmin'})
5 .skipZeroOrMore()
6 .state({node: '?alt', kont: '?k', lkont: '?lk'})
7 .not().endIf({kont: '?k', lkont: '?lk'}).star()
8 .fCall({name: 'addNotice'})

```

Listing 6.10: Policy 4 in JS-QL

Discussion

While this policy finds all cases where `isCMSAdmin` is false, it will not detect calls to `addNotice` outside this test. We can solve this by finding all calls to `addNotice`, but this leads to false positives. The situation would be improved if a means to express the *XOR* relation between results of the JS-QL policies existed. If we had this kind of mechanism at hands, we could search for all calls to `addNotice` and the calls to `addNotice` that happen in the true branch of `isCMSAdmin` and remove all states that occur in both results. The result of this removal would then contain only the violations of the policy. Currently, no operation for combining queries is supported, as this would require an other layer of abstraction over query results. Although possible, the combining of queries is out of the scope of this dissertation.

6.2.2 Public outputs do not depend on a user’s password, unless it has been cryptographically hashed

Users want to prevent sensitive information from leaking to other users. It is therefore not desirable that sensitive information about passwords is leaked in any way to public outputs. This leak of information can be implicit. Imagine a

situation where a malicious piece of code checks if the length of the password is larger than 5. If the condition is true the output will display 1, otherwise the output is 0. This also reveals information about the password, and thus should be treated as a violation. The name for this kind of information flow is *implicit flow*.

```
1 var password = getPassword();
2 //computeHash(password);
3 var message;
4 if(password.length() > 5){
5     message = 1;
6     print(message);
7 }
8 else{
9     message = 0;
10    print(message);
11 }
```

Listing 6.11: The output depends on the password example

Pidgin policy

Since PidginQL works on the the dependence graph of a program, the 'depends' relation is easily checked. In the graph there must be no path between the retrieval of the password and an output, unless `computeHash` was called. *Declassification* happens when calling this method, which means that from then on the password is sanitized and ready to flow to an output. The policy in listing 6.12 displays how this is expressed in the PidginQL language.

```
1 let passwords = pgm.returnsOf("getPassword") in
2 let outputs   = pgm.formalsOf("writeToStorage") U
3               pgm.formalsOf("print") in
4 let hashFormals = pgm.formalsOf("computeHash") in
5 pgm.declassifies(hashFormals, passwords, outputs)
```

Listing 6.12: Policy 5 in PidginQL

JS-QL policy

The scenario for which we write a policy in JS-QL is as follows: An output depends on the password when the password is used in a conditional expression. In one or more of the branches of this conditional expression an output function is then called. The example code on which we test our policy is listed in listing 6.11. We look for a state in the graph where the password is returned, and we store the address in `?addr`. The program then continues for some states in which the `computeHash` method is *not* called with the password as an argument

(lines 3-16). We then match a state representing a conditional node, in this case an `IfStatement` for which we bind the true branch to `?cons` and the false branch to `?alt`.

Note that in the JIPDA abstract state graph, all evaluation steps are visible in the graph. This gives us an opportunity to check if somewhere in the condition of the conditional the password is used before the actual branching happens. The `variableUse` predicate on line 19 performs this check. It matches any state in which a variable is used. The declarative nature of the predicates allows us to pass the address of the variable as a metavariable, so that we can specify that we only want to match the uses of the variable whose address is already captured in `?addr`. When this results in a match, we know that the variable has been used in the evaluation of the condition of the conditional.

Finally, we proceed by checking if an output function (`print` in this case) is called *inside* one of the branches of the conditional. We do this by matching the nodes of states to the already bound `?cons` and `?alt`. A match indicates that that state is the beginning of the true branch or false branch respectively. For these branches, we capture the context and current stack in two additional metavariables `?k` and `?lk`. These will be needed on line 26 to indicate that we want to find the call to `print` *before* the branch ends. This policy, found in listing 6.13, can be made more general by writing a predicate which captures all conditionals instead of just `IfStatements`.

```

1 G.skipZeroOrMore()
2 .procedureExit({functionName:'getPassword', returnAddr : '?addr'
3   })
4 .not()
5 .state({
6   node:{
7     expression: {
8       callee: { name:'computeHash' },
9       arguments: '?args'
10    },
11    properties: {
12      '?arg' : prop('memberOf', '?args'),
13      '?firstName': '?arg.name'
14    },
15    lookup:{ '?firstName' : '?addr' }
16  }).star()
17 .ifStatement({cons:'?cons', alt:'?alt'})
18 .skipZeroOrMore()
19 .variableUse({addr:'?addr'})
20 .skipZeroOrMore()
21 .lBrace()
22 .state({node:{this:'?cons'}, kont:'?k', lkont:'?lk'})

```

```

23   .or()
24   .state({node:{this:'?alt'}, kont:'?k', lkont:'?lk'})
25   .rBrace()
26   .not().state({kont:'?k', lkont:'?lk'}).star()
27   .fCall({name: 'print'})

```

Listing 6.13: Policy 5 in JSQL

Discussion

Expressing dependencies in JS-QL is challenging. However, we were able to fully express the PidginQL policy for checking if an output depends on a user password. We can conclude that the JS-QL policy is more verbose than its PidginQL counterpart, but it is also more flexible in its notation.

6.2.3 A database is opened only after the master password is checked or when creating a new database

A database may contain sensitive information, so it is important that only authorized people can access this information. It therefore is necessary to restrict access to the database, unless upon creation or when the correct credentials can be presented.

Pidgin policy

The PidginQL query in listing 6.14 describes the query pattern in pseudocode. All nodes corresponding to checks of the master password are stored in the `check` variable. Lines 2 and 3 remove these nodes from the graph when the condition is true (i.e. when the master password is correct). Finally, the nodes where the creation of a new database occurs are also deleted from the graph, resulting in a graph which consists of only nodes that represent the opening of the database. If the graph is empty, then no violations are found.

```

1 let check = (all checks of the password)
2 let checkTrue = pdg.findPCNodes(check, TRUE) in
3 let notChecked = pdg.removeControlDeps(checkTrue) in
4 let newDB = (method to create database)
5 let openDB = (method called to open the database)
6 notChecked.removeNodes(newDB) and openDB is empty

```

Listing 6.14: Policy 6 in PidginQL

JS-QL policy

We created 2 JS-QL policies that provide full coverage for the problem that is presented in this section, listed in listing 6.15. The problem can be alternatively stated as follows: Find all calls to `openDatabase` that are not inside the true branch of a conditional that checks if the master password is correct. When described like this, the vulnerability is much more intuitive to express in JS-QL. The policy can be split up in two parts: The first part will skip to an `IfStatement` of which we bind the true branch to `?cons`, as in the previous example. We then again check if the condition of that statement uses the `isMasterPassword` to verify the correctness of the password. We want to look into all states for which this condition does not hold, which is described on line 7. In this case all calls to `openDatabase` are prohibited, except inside the `newDatabase` function.

This policy catches all violations *after* the first matching `IfStatement`. That is why there is the need for a second part in the policy, depicted on line 16. The detection of all calls to the `openDatabase` function completes this policy, but adds as a side effect that it will add false positives. These false positives will be the calls to `openDatabase` that occur when the master password is correct. This confirms the need for the *XOR* relation, as described in the previous section.

```
1 G.skipZeroOrMore()
2 .lBrace()
3   .lBrace()
4     .ifStatement({cons:'?cons'})
5     .skipZeroOrMore()
6     .fCall({name:'isMasterPassword'})
7     .not().state({node:'?cons'}).star()
8     .beginApply({name:'?name', lkont:'?lk', kont:'?k',
9                 filters:[
10                    cond('!==' , '?name', 'newDatabase')
11                ]})
12     .not().endApply({lkont:'?lk', kont:'?k'}).star()
13     .fCall({name:'openDatabase'})
14   .rBrace()
15   .or()
16   .fCall({name:'openDatabase'})
17 .rBrace()
```

Listing 6.15: Policy 6 in JS-QL

Discussion

This policy was challenging to express in JS-QL. Although able to detect all violations, the JS-QL policy will result in false positives. At the moment, it is not

possible to express a JS-QL query for this policy which only detects violations without false positives.

6.2.4 Conclusion

In this section we expressed 3 security vulnerabilities in the PidginQL language and JS-QL. Table 6.2 indicates that not all three policies were easily expressible. We are able to express all 3 policies in JS-QL, but 2 of them will have results containing false positives. These two policies each consisted of two separate queries. If we wish to attain a resultset only containing violations and no false positives, we could take the exclusive disjunction of the resultsets of these separate queries.

The PidginQL language is best at expressing policies that deal with the dependencies between nodes in their program dependence graph. This type of graph is very powerful to check the control and data flow between two parts of code [11], but it is more difficult to use it to detect more general properties about a program. For JS-QL, it is the other way around. Our approach allows us to detect a wide range of general and complex properties about a program, but it sometimes has troubles detecting dependencies between states with only one policy. PidginQL may be powerful in finding dependencies as described above, it does however not return much meaningful information about the found violations. Where JS-QL returns all violating nodes marked in a GUI, PidginQL just indicates whether there are violations or not. It doesn't specify which nodes are violating the policy.

Language	Policy 4	Policy 5	Policy 6
PidginQL	✓	✓	✓
JS-QL	○	✓	○

Legend: ✓: Fully expressible, ○: Expressible with false positives

Table 6.2: Expressiveness in JS-QL and Pidgin

Another restriction in PidginQL is that there is no way to reason about the internals of a state in the graph. Our language allows the programmer to query information in the graph on the level of each state. We can dig inside a state at any time and specify the information we wish to obtain in some user-declared metavariables. This is not possible in PidginQL. This expressiveness and flexibility brings along that JS-QL queries and policies will often be more verbose.

While JS-QL can be used for many different domains, PidginQL is especially strong in the domain of querying for dependencies between nodes.

6.3 The ConScript language

In this section we express 3 security vulnerabilities originally presented in ConScript [28]. ConScript is a client-side advice implementation for security. The language allows the hosting page to express fine-grained application-specific security policies that are enforced at runtime.

6.3.1 No string arguments to setInterval, setTimeout

In JavaScript, `setInterval` and `setTimeout` take a callback function as a first argument that is fired after a certain interval of time. Surprisingly, a string argument can also be passed as the first argument, as indicated in listing 6.16. This allows potential attackers to pass malicious code as a string argument to `setInterval/setTimeout`, which can lead to security threats.

```
1 var f = function() {}
2 var i = 1;
3 var s = "stringgy"
4 var o = {};
5 setTimeout(i, interval);
6 setTimeout(s, interval); //Violation
7 setTimeout(o, interval);
8 setTimeout(f, interval);
```

Listing 6.16: No string arguments to setTimeout

ConScript policy

ConScript is an aspect-oriented advice language that is able to detect security violations such as the one depicted in listing 6.16. The aspects are written in JavaScript, which enables the programmer to make full use of the language. The ConScript language also provides a typesystem which assures that the policies are written correctly, as can be seen in listing 6.17 on line 1. Lines 10-11 depict the actual registration of the advice on the `setInterval` and `setTimeout` functions. When called, the `onlyFnc` function will be triggered instead, which checks if the type of the argument is indeed of type “function”. `curse()` has to be called within the advice function, disabling the advice in order to prevent an infinite loop. We consider this as a small hack, since it has no additional semantic value for the policy itself.

```
1 let onlyFnc : K x U x U -> K =
2 function (setWhen : K, fn : U, time : U) {
3   if ((typeof fn) != "function") {
4     curse();
```

```

5         throw "The time API requires functions as inputs.";
6     } else {
7         return setWhen(fn, time);
8     }
9 };
10 around(setInterval, onlyFnc);
11 around(setTimeout, onlyFnc);

```

Listing 6.17: Policy 7 in ConScript

JS-QL policy

As we can not reason about actual concrete values in abstract interpretation in our approach, writing a policy that only allows strings seems more challenging. This is not the case however, because the lattice we use gives us information about the type of the value of variables. A string for example is indicated by the lattice value `{Str}`. We can then define a `isString` helper function which checks whether a variable *may* be of type `String` or not. The JS-QL policy in listing 6.18 uses this function to determine whether the looked up value of the `?name` variable is of type `String` or not. The policy looks for a call of the `setTimeout` function and binds its arguments to `?args.memberOf`, which creates a new substitution set for each of the elements in the list that it takes as an argument. This allows us to inspect and check each individual argument `?arg` of the `setTimeout` function. We take the name of the argument and look up its value in the lookup clause. What remains is to filter out the string arguments, as already discussed above. This policy will only detect the actual violation on line 6 in listing 6.16.

```

1 G.skipZeroOrMore()
2 .fCall({
3   name: 'setTimeout',
4   arguments: '?args',
5   properties: {
6     '?arg' : prop('memberOf', '?args'),
7     '?name': '?arg.name',
8   },
9   lookup: {'?name': '?lookedUp'},
10  filters: [
11    cond('isString', '?lookedUp')
12  ]
13 })

```

Listing 6.18: Policy 7 in JS-QL

Discussion

Both approaches are able to express the security vulnerability in a concise way. The JS-QL policy however is more readable than its ConScript counterpart, as it requires less boilerplate code and does not use type system annotations.

6.3.2 HTTP-cookies only

Servers often store state information on the client in the form of cookies. They do this to avoid the cost of maintaining session state between calls to the server. Cookies may therefore contain sensitive information that may only be accessed by the server, so it is necessary to prohibit reads and writes to the client's cookies. These are stored in the global `document.cookie` object. Listing 6.19 gives an example of possible violations.

```
1 var doc, cookie1, cookie2, cookie3, badFunc;
2 badFunc = function() {
3   var bad;
4   bad = document.cookie;           //Violation (read)
5   return bad;
6 }
7
8 cookie1 = document.cookie;         //Violation (read)
9 doc = document;
10 cookie2 = doc.cookie;              //Violation (read)
11 cookie3 = badFunc();               //Violation (read)
12 document.cookie = {value:"bad"}    //Violation (write)
```

Listing 6.19: HTTP-cookies only example

ConScript policy

In ConScript, the policy can be enforced with only a few lines of code. Listing 6.20 wraps reads and writes of the "cookie" field of `document` in the `httpOnly` advice. An error is thrown when a violation against this policy is encountered.

```
1 let httpOnly:K->K=function(_:K) {
2   curse();
3   throw "HTTP-only cookies";
4 };
5 around(getField(document, "cookie"), httpOnly);
6 around(setField(document, "cookie"), httpOnly);
```

Listing 6.20: Policy 8 in ConScript

JS-QL policy

Writing an equivalent JS-QL policy proves to be more verbose. The reason for this is that we only work with our own embedded DSL to query the information in the JIPDA graph. While the `getField` and `setField` in 6.20 handle the lookup of the address of `document.cookie`, we have to manually specify that we want to store the address in metavariable `?cookieAddr` and try to match it with the address of the `?name` metavariable, which we assign to the same metavariable `?cookieAddr` to filter out variables with a different address. The JS-QL policy in 6.21 specifies that it only detect writes (the first `assign` predicate) and reads (the `procedureExit` and second `assign` predicate) of the `?name` variable which points to the address of the global `document.cookie` object. The `assign` predicate matches the left or right name of the assignment and performs a lookup. The `procedureExit` is an extra predicate which marks all returns of functions that return a value that again points to the address of the global `document.cookie` address.

```
1 G.skipZeroOrMore()
2 .lBrace()
3   .assign({leftName:'?name',
4           lookup:
5             {
6               '_global.document.cookie' : '?cookieAddr',
7               '?name'                   : '?cookieAddr'
8             }
9           })
10  .or()
11  .assign({rightName:'?name',
12          lookup:
13            {
14              '_global.document.cookie' : '?cookieAddr',
15              '?name'                   : '?cookieAddr'
16            }
17          })
18  .or()
19  .procedureExit({returnName:'?name',
20                 lookup:
21                   {
22                     '_global.document.cookie' : '?cookieAddr',
23                     '?name'                   : '?cookieAddr'
24                   }
25                 })
26 .rBrace()
```

Listing 6.21: Policy 8 in JS-QL

Discussion

The JS-QL policy for detecting access to cookies is more verbose than the policy written in ConScript. This is because ConScript has access to the getter and setter methods of variables, whereas JS-QL can only reason about the information which is contained in the abstract state graph. JS-QL thus needs to manually look for access violations to `document.cookie`, instead of just checking if a getter or setter of that variable is called.

6.3.3 Prevent resource abuse

Malicious scripts can prevent parts of a program to be accessible by users. A website or plugin can exploit resources by consecutively displaying popup windows. This is a form of resource abuse, namely the abuse of modal dialogs. This can be prevented by prohibiting calls to functions that create these resources.

ConScript policy

The ConScript policy is similar to the policy discussed in section 6.3.2. Calls to `prompt` and `alert` are wrapped in an advice which throws an error. Listing 6.22 shows the source code of the policy.

```
1 let err : K -> K = function () {  
2     curse();  
3     throw 'err';  
4 };  
5 around(prompt, err);  
6 around(alert, err);
```

Listing 6.22: Policy 9 in ConScript

JS-QL policy

Wrapping an advice around a function to detect calls to that function can be used to prevent the invocation of that function. To find function invocations in JS-QL, one just has to write a policy consisting of a `fCall` predicate. This predicate has to be configured to return all relevant information we need about the function call. In listing 6.23 we can see that a function call (AST) node contains fields for its `procedure` and its `arguments`. We bind these to `?proc` and `?args` respectively. We then further define an extra metavariable `?name` in the `properties` clause of the predicate, which maps to the name of the earlier defined `?proc`. Once we have the information about the function that is invoked, we can look up

its address and compare it to the address of the global alert (or prompt) function. When these are equal, the substitutions for the detected function call will be added to the results.

```
1 G.skipZeroOrMore()
2 .fCall({
3   procedure: '?proc',
4   arguments: '?args',
5   properties: {
6     '?name' : '?proc.name'
7   },
8   lookup: { '?name': '?alertAddress',
9             '?_global.alert': '?alertAddress' }
10 })
```

Listing 6.23: Policy 9 in JS-QL

Discussion

We conclude that JS-QL is capable of expressing a policy for detecting resource abuse, and that the resulting queries are more about as verbose as their equivalent in ConScript. The result of the JS-QL query returns the exact positions in the program where a violation occurs, whereas ConScript only throws an error if an actual violation is encountered.

6.3.4 Conclusion

In this section we expressed 3 security vulnerabilities in the ConScript language and JS-QL. It is not straightforward to compare both approaches, as ConScript checks for policy violations using dynamic analysis. We can however compare the expressiveness of the policies written in each language. Table 6.3 shows that we are able to express all 3 ConScript policies in JS-QL.

The ConScript language applies advices around function calls, changing the behavior of the program if the function call was prohibited. The aspect-oriented approach allows ConScript to specify what actions that need to be taken when a violation is detected. We can not express this in JS-QL, but this is also not necessary since we detect violations at compile-time, rather than at runtime. Field accesses can also be expressed as function calls (`getField` and `setField` in listing 6.20), so ConScript can reason about getting and setting values as well. JS-QL can also reason about these things, but it has access to a lot more information thanks to the abstract state graph.

The advice functions written in ConScript have full access to the JavaScript language, making them very flexible in behaviour. By using JavaScript instead

Language	Policy 7	Policy 8	Policy 9
Gatekeeper	✓	✓	✓
JS-QL	✓	✓	✓

Legend: ✓: Fully expressible

Table 6.3: Expressiveness in JS-QL and ConScript

of a DSL, the policies themselves are also quite verbose, since for each policy a JavaScript function has to be created. This does allow users of ConScript to define properties and filters, as in JS-QL. However, the advice approach limits ConScript to detect only function calls, which certainly is a limitation because it reduces expressiveness. Querying for multiple sequential lines of code is also hard to do in ConScript. Where a JS-QL policy could easily be written to detect a function call to method X after reading variable Y , ConScript has to define variables that function as a “boolean”. The variable will be set to true when Y is read. The advice around X then has to check the value of Y before deciding what action to perform.

We argue that JS-QL queries are more expressive when it comes down to the detection of different kinds of program states. The language also proves flexible in terms of specifying properties and filters, but is not as flexible as ConScript because the latter has full access to the JavaScript language once an advice is triggered. Both languages are quite verbose because of the expressiveness they provide.

6.4 Evaluation

We evaluated the JS-QL language by expressing 9 different security vulnerabilities originating from 3 different papers. This section evaluates the tool presented in the dissertation by discussing the advantages and limitations of the query language.

6.4.1 Advantages

Granularity of queries and policies

A key advantage of the JS-QL tool is the ability for programmers to define queries and policies as general or specific as they want. Starting from the `state` predicate, a user can express complex patterns that fit his needs and wrap them in a self-named predicate. Flexibility is key in these predicates since the user can

specify which properties he exposes through the predicate. These properties can then be queried by passing metavariables as arguments, which will later be bound when a match is found. Literals and metavariables that are already bound act as filters for the predicates, as in any declarative language.

Negation

Negation can be useful when expressing actions that should not happen at a certain moment in a query. This was illustrated in section 6.2.1, where a function call needed to be detected before the end of a conditional branch. JS-QL, in contrast to many other query languages, offers this expressiveness, albeit in a limited way.

Flexibility

The JIPDA graph contains states with information of arbitrary depth. Therefore, the tool has to provide access to these levels of information. This flexibility again opens up opportunities because we are not bound to one particular graph type. Hypothetically, all types of graphs that contain information in its edges and nodes can be used in the tool with little to no modification of the tool itself. Only a reification layer of the new graph should be provided, mapping the states of the graph to the format our tool uses.

Recursion

Another non-trivial feature of the JS-QL tool is the possibility to recursively define queries. This type of queries are especially useful when one wants to follow a trace of information starting at a certain point. For example, an interesting use for recursive queries is to trace all aliases of a certain variable. The result then shows all states in the graph where the original variable is aliased. Along with the marked nodes in the graph, a table containing all substituted metavariables is also displayed. We believe this representation makes the results comprehensive for users.

6.4.2 Limitations

Other approaches might modify the graph by deleting states and edges to obtain a new graph. This new graph then only consists of information needs to be reasoned about. Our tool currently does not provide this functionality.

Another feature that would amplify the expressive power of the tool would be some means to combine results of multiple queries, such as the use of logical arithmetics. Expressing the disjunction or conjunction of two queries would

greatly improve the expressiveness of JS-QL. An example of this was given in subsections 6.2.1 and 6.2.3.

Although negation is already supported, it only works for single `states`. We would also add to the expressiveness of the language if we were unrestricted while expressing negation. This is a topic for future research.

6.4.3 Performance

The time to generate the abstract state graph depends on the size of the input program, and the time needed by the solver algorithms depends on the size of the query (i.e. number of pattern states). All of the vulnerabilities expressed in this chapter could be checked in under 3 seconds. For this dissertation however, performance is of lesser importance.

6.4.4 Conclusion

The combination of abstract state graphs and regular path expressions prove to be an effective means to obtain program information and define security policies. We validated our tool by expressing a range of different security vulnerabilities in the JS-QL language. We discussed the differences in our language and three other languages for expressing security vulnerabilities. By evaluating our tool, we identified the advantages and limitations of our approach. We can conclude that the JS-QL tool can be used to express a wide variety of security vulnerabilities in a readable and flexible way, but that it is still limited in expressiveness for certain types of policies, such as policies for detecting dependencies between two states.

Chapter 7

Conclusion and future work

In this dissertation proposed a query-based technique for detecting security vulnerabilities in JavaScript programs. Unlike most existing techniques, ours can be configured to detect vulnerabilities that are specific to a single application. To this extend we investigate JS-QL, an expressive specification language that enables users to write succinct and application-specific queries instead of using pre-encoded rules. Our language matches queries against the output graph of a statically analyzed program. More specifically, we use abstract interpretation as a static analysis technique to generate an abstract state graph representing a program.

The JS-QL tool combines abstract interpretation with JS-QL, a novel program specification language that enables developers to test their applications against these vulnerabilities. JS-QL is a domain-specific language embedded in JavaScript and is based on the concept of regular path expressions. These expressions are similar to traditional regular expressions, except that they can be applied to find certain paths in a graph instead of finding patterns in a string. Other approaches are described in related work (Sections 2.2 and 2.3), but none of them use abstract interpretation to model the flow of programs.

We evaluated our approach by comparing our language with other languages for expressing security vulnerabilities in terms of expressiveness. The results of the evaluation indicate that the static analysis of our technique is sufficiently powerful while its specification language is sufficiently expressive for application-specific vulnerabilities commonly found in related work. We also provide a tool together with a minimalistic user interface serving as a means to apply JS-QL queries to JavaScript programs, reporting all results of a query in both a visual (graph) representation and a textual representation.

We conclude from our experiments that our language is apt for specifying several types of security vulnerabilities. These specifications are often more readable, concise and equally expressive compared to their notation in other languages.

7.1 Technical limitations of the approach

This section discusses the limitations of the tool. We seek to find appropriate solutions for all of the following limitations of the tool in future work.

Negation

As discussed in section 4.1, negation is supported by the JS-QL language. The current implementation however is limited to the negation of only one state, which sometimes does not suffice. Consider a situation in which a state in the state graph must be matched with all but two specific states `stateA` and `stateB`. To match this state, it would be convenient to be able to express a pattern in JS-QL like

```
not().lBrace().stateA().or.stateB().rBrace()
```

indicating that neither states must be matched for a certain state in the state graph. This functionality is not available in the current implementation of JS-QL.

One could also argue that it would be useful to specify the negation of a single value in a state. In this way, one could for example express that they wish to find all variable declarations, except for variables with name `'a'`. The relevant code in the state map would then be: `{name: '¬a'}`. Although this notation might be useful, JS-QL already supports queries with the same semantic value, by using a simple filter indicating that the name can not be equal to `'a'`.

Performance

Our current implementation has some computational overhead as each state edge label `el` and pattern label `tl` can be matched multiple times in the algorithm. Each match is a computationally heavy operation, which means that we should try to avoid matching `el` and `tl` more than once. This could be done by memoizing the substitutions between all already matched pairs of state and pattern, decreasing the computational overhead drastically. This approach would make the tool scale in two ways: (i) The JavaScript programs to be queried can be of larger size because (ii) the algorithms used would saturize more quickly, resulting in faster query results. Currently, all programs and queries tested run within reasonable time (< 3 seconds), but we expect that for larger programs and queries the run-time of the tool would increase significantly. However, the goal of this thesis was to investigate whether regular path queries can be used to effectively specify and detect security vulnerabilities, rather than to build a performant tool to process these queries.

7.2 Future research

This section discusses the subjects of interest for future research. We believe that research in these areas can be fruitful for both the JS-QL language as well as other approaches for detecting security vulnerabilities.

A library of security vulnerabilities

Our experiments show how security vulnerabilities originating from related work can be expressed in JS-QL. Gathering more security vulnerabilities to express will grant us insight on several recurring patterns used to exploit application flaws. The exploration of vulnerabilities and vulnerability types can lead to the creation of more specific and precise constructs in JS-QL that are optimal for expressing these security vulnerabilities.

Querying other program representations

JS-QL was designed to work on the JIPDA state graph. We would like to investigate how much work is needed to port JS-QL to support other graphs. Hypothetically, only the matching process has to be altered, as other graphs will contain information that is structured differently.

Combining results

A great addition to JS-QL would be the ability to combine results of queries. This would make it easier for the user to detect multiple vulnerabilities at the same time, and it would make the language more expressive. Combining results could be implemented as a simple conjunction operation, but could also be defined as a more complex operation between results, such as an exclusive disjunction for example. The usefulness of the latter has already been proven in our experiments (6.2.1).

7.3 Concluding remarks

We started this dissertation by investigating which approach would fit best for detecting security vulnerabilities in JavaScript programs. We presented the JS-QL tool, a tool for expressing and checking security vulnerabilities against an abstract state graph. The tool uses the novel JS-QL language, which is based on regular path expressions.

We believe that our tool represents a step in the right direction for allowing users to preventively detect security vulnerabilities in their JavaScript applications. By shifting the emphasis from general policies to application-specific policies, security vulnerabilities can be expressed in a more fine-grained way when using the JS-QL tool.

Appendices

Appendix A

JS-QL policies and predicates

```
1 G.skipZeroOrMore()
2 .state({node:{
3     expression:{
4         callee : {name : 'close'},
5         arguments: '?args'
6     }},
7     properties:{
8         '?arg' : prop('memberOf','?args'),
9         '?argName': '?arg.name'
10    },
11    lookup:{
12        '?argName': '?argAddr' //Match address of the file
13    }
14 })
15 .not()
16 .state({node:{
17     expression:{
18         callee : {name : 'open'},
19         arguments: '?args2'
20     }},
21     properties:{
22         '?arg2' : prop('memberOf','?args2'),
23         '?argName2': '?arg2.name'
24    },
25    lookup:{
26        '?argName2': '?argAddr'
27    }
28 }).star() //Zero or more states
29 .state({node:{
30     expression:{
31         callee : {name : 'access'},
32         arguments: '?args3'
33    },
```

```

34     properties:{
35         '?arg3' : prop('memberOf','?args3'),
36         '?argName3': '?arg3.name'
37     },
38     lookup:{
39         '?argName3': '?argAddr' //Match address of the file
40     }
41 })

```

Listing A.1: A query for detecting accesses to closed files

```

1  JSQL.prototype.writeToBuiltinObjectPrototype = function(obj){
2      var obj = obj || {};
3      var states = [];
4      var frozenObjects = ['Array', 'Boolean', 'Date', 'Function', '
        Document', 'Math', 'Window', 'String'];
5      var ret = this.lBrace();
6      var objProps = this.getTmpIfUndefined();
7      for(var i = 0; i < frozenObjects.length; i++){
8          var s = {};
9          this.setupStateChain(s, ['node', 'expression', 'left', '
                properties'], objProps);
10         this.setupStateChain(s, ['node', 'expression', 'left', '
                mainObjectName'], frozenObjects[i]);
11         this.setupFilter(s, 'contains', objProps, 'prototype');
12         this.finalize(s, obj);
13         states.push(s);
14     }
15     for(var j = 0; j < states.length; j++){
16         if(j !== states.length - 1){
17             ret = ret.state(states[j]).or()
18         }
19         else{
20             ret = ret.state(states[j]).rBrace();
21         }
22     }
23     return ret;
24 }

```

Listing A.2: The assign predicate

```

1  obj = obj || {};
2  var s1 = {};
3  var s2 = {};
4  var newObj = {};
5  var x = this.getTmpIfUndefined(obj.x);
6  var y = this.getTmpIfUndefined(obj.y);
7  var flow;
8

```

```

9   if(obj.rec){
10      flow = this.getRecVar(obj.rec);
11   }
12   else{
13      flow = this.getTmpIfUndefined();
14   }
15
16   newObj.x = flow;
17   newObj.y = y;
18   newObj.rec = obj.rec;
19
20   this.setupStateChain(s1, ['node', 'expression', 'right', 'name'],
      x); //alias
21   this.setupStateChain(s1, ['node', 'expression', 'left', 'name'],
      y); //leaked
22   this.setupStateChain(s2, ['node', 'expression', 'right', 'name'],
      x); //alias
23   this.setupStateChain(s2, ['node', 'expression', 'left', 'name'],
      flow); //leaked
24
25   return this .lBrace()
26       .state(s1) //assign from x to y
27       .or()
28       .state(s2) //assign from x to tmp
29       .skipZeroOrMore()
30       .rec(newObj, this.taintedBy)
31       .rBrace();
32
33 }

```

Listing A.3: The taintedBy recursive policy

```

1  JSQL.prototype.writeToBuiltinObjectPrototype = function(obj){
2    var obj = obj || {};
3    var states = [];
4    var frozenObjects = ['Array', 'Boolean', 'Date', 'Function', '
      Document', 'Math', 'Window', 'String'];
5    var ret = this.lBrace();
6    var objProps = this.getTmpIfUndefined();
7    for(var i = 0; i < frozenObjects.length; i++){
8      var s = {};
9      this.setupStateChain(s, ['node', 'expression', 'left', '
        properties'], objProps);
10     this.setupStateChain(s, ['node', 'expression', 'left', '
        mainObjectName'], frozenObjects[i]);
11     this.setupFilter(s, 'contains', objProps, 'prototype');
12     this.finalize(s, obj);
13     states.push(s);
14   }

```

```
15  for(var j = 0; j < states.length; j++){
16      if(j !== states.length - 1){
17          ret = ret.state(states[j]).or()
18      }
19      else{
20          ret = ret.state(states[j]).rBrace();
21      }
22  }
23  return ret;
24 }
```

Listing A.4: The writeToBuiltinObjectPrototype policy

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