Abstract—Although iOS is the second most popular mobile operating system and is often considered the more secure one, approaches to automatically analyze iOS applications are scarce and generic app analysis frameworks do not exist. This is on the one hand due to the closed ecosystem putting obstacles in the way of reverse engineers and on the other hand due to the complexity of reverse engineering and analyzing app binaries. Reliably lifting accurate call graphs, control flows, and data dependence graphs from binary code, as well as reconstructing object-oriented high-level concepts is a non-trivial task and the choice of the lifted target representation determines the analysis capabilities. None of the various existing intermediate representations is a perfect fit for all types of analysis, while the detection of vulnerabilities requires techniques ranging from simple pattern matching to complex inter-procedural data flow analyses. We address this gap by introducing liOS, a binary lifting and analysis framework for iOS applications that extracts lifted information from several frontends and unifies them in a "supergraph" representation that tolerates missing parts and is further extended and interlinked by liOS "passes". A static analysis of the binary is then realized in the form of graph traversal queries, which can be considered as an advancement of classic program query languages. We illustrate this approach by means of a typical JavaScript/Objective-C bridge, which can lead to remote code execution in iOS applications.

I. INTRODUCTION

iOS is the second most spread mobile operating system and has ever since enjoyed a reputation as the "more secure" system, compared to Android. While this might actually be true when considering the security features of the iOS hardware and software stack, a substantial part of this reputation originates from the fact that the app ecosystem is largely under exclusive control of Apple. The bar for distributing malware is much higher due to the obligation to enroll in the Apple developer program, the AppStore review process, and Apple’s ability to centrally revoke an app. However, malware is not the only threat to users’ security and privacy, and for iOS it might even be the less relevant one.

The closed nature of the app ecosystem and the fact that iOS applications are much harder to reverse engineer – let alone repackage – than Android apps has drawn the attention of many researchers and hackers away from iOS to platforms that are easier to assess and attack. But iOS applications are not necessarily more secure than their Android equivalents. In contrast to Android apps which mostly consist of memory-safe bytecode and are assigned a separate user ID per app, iOS apps typically run under the same user account mobile and are confined by the Sandbox which enforces mandatory access control profiles on them – a mechanism which has been shown to be flawed in the past [3]. For users, the internals of an iOS app remain highly unclear and trust in an app relies exclusively on the AppStore review process whose details are not publicly known and which has been circumvented in the past [17]. Thus, ways to automatically analyze iOS apps for vulnerabilities are urgently needed to increase transparency for the user and to build trust in the ecosystem.

Precise automated static analysis of binary iOS applications is however not trivial and only few contributions have been made so far by the research community [5], [6]. First, the majority of iOS apps are not easily accessible due to the FairPlay DRM encryption which is supposed to prevent apps from being copied. Although not insurmountable, the mechanism is a considerable hurdle for researchers to get their hands on a large corpus of iOS apps, as discussed by Orikogbo et al. [13]. Further, iOS apps do not come in form of easily analyzable bytecode, but in form of native ARM binaries that make it more difficult and error-prone to recover high-level information such as function calls and variable aliases. Above cited research has shown that it is still possible to detect specific vulnerabilities by analyzing the app binary but up to date, there is no generic static analysis framework available that allows to detect arbitrary vulnerability pattern in iOS apps. Specifically, the following challenges have not been satisfactorily solved:

- Lifting iOS apps to a representation that covers both the semantics of low-level assembly as well as high-level object oriented concepts
- A thorough approach to take into account the semantics of the Objective-C/Swift runtime
- A generic way to statically analyze iOS apps for different types of vulnerabilities

In this paper, we address these challenges and propose liOS, a framework for static binary analysis that can detect configuration-, control flow-, and data flow-based vulnerabilities. liOS is extensible in that it accepts input from various frontends and combines them in a single graph-based representation, called the supergraph. While some frontends operate directly on the disassembly, others lift the aarch64 binary to the LLVM intermediate representation (IR) to support further analysis techniques from the existing LLVM ecosystem, or extract higher-level information such as class hierarchy, methods, and variables from the binary. The graph-based representation allows us to combine the output of these frontends into one unified representation, linking information
from all frontends with each other. This is especially useful when dealing with an incomplete representation – a recurring problem with binary lifting, which is never fully accurate for applications of realistic size and complexity. Further, it allows us to map the implementation of static analysis methods in liOS to the problem of finding a graph traversal, i.e. a set of paths in the supergraph with specific properties. This approach decouples the actual artifact (in our case, an iOS app) from the overall analysis framework and allows to plug in further analysis techniques at a later time by simply adding graph traversals. We give details on the supergraph construction and illustrate how typical static analysis problems can be solved with graph traversals. Through a typical remote code execution vulnerability, we illustrate how liOS is able to discover complex vulnerabilities in iOS binaries.

Section II guides through the overall process of automated reverse engineering and analysis of iOS apps, conducted by liOS. Section III introduces the concept of the supergraph and shows the contributions of liOS (marked corners). In this section, we will walk through this process and explain how liOS converts a binary iOS application into a representation suited for program analysis.

**A. Unzipping the IPA and Loading the Binary**

We start with a decrypted .ipa file that is either directly exported as an archive from XCode or has been dumped from a physical device. When installed from the Apple AppStore, Mach-O sections will be encrypted with the public key that is assigned to the Apple account associated with the physical device, whose corresponding private key is managed by the Secure Enclave TEE on the phone. This mechanism is part of Apple’s FairPlay DRM and ways to circumvent it are known since 2008. As decryption of sections is already done by the binary loader when mapping sections to memory segments, it is easy enough to load the app into memory, dump its segments in clear text and re-assemble an unencrypted binary. Orikogbo et al. have shown in [13] that this process can be fully automated and although their success rate when decrypting the binary is only about 51%, our experience is that a much higher (>95%) success rate can be achieved by using more recent devices and the Frida DBI framework.

The actual analysis process of liOS begins with extracting the Mach-O binary from the zip-compressed .ipa file, along with further files which are relevant for the analysis at a later time, such as Info.plist. The aarch64 binary is extracted from the fat Mach-O and passed to the loader of liOS which parses the binary’s load commands to reconstruct segments (LC_SEGMENT), symbol tables (LC_SYMTAB and LC_DYSYMTAB), and function boundaries (LC_FUNCTION_STARTS). The detection of function boundaries in a binary blob in the absence of debug symbols is a notoriously difficult problem and modern disassemblers apply heuristic approaches such as BYTEWEIGHT [1], FID [16] or FLIRT [7] to determine where a function starts. Luckily, in contrast to PE and ELF binaries, the Mach-O format includes an LC_FUNCTION_STARTS load command in its header which points to the address of a list of function start pointers. This list is implemented as a zero-terminated sequence of ULEB128-encoded [4, pp. 221] addresses indicating the start of all functions, from the lowest to the highest address. While this function list is mainly used for producing meaningful output for debuggers or stack traces, it is not to be confused with debug symbols which would get removed from the binary by the strip command. The function list remains intact even in stripped binaries and allows us to precisely and efficiently reconstruct function boundaries from any iOS application.

**B. Class hierarchies and Selectors**

iOS apps are written in either Swift of Objective-C which are both executed in the Objective-C binary runtime, but may also include C/C++ libraries. A subset of the functions in the aforementioned function list will thus map to methods of Objective-C or Swift classes and reconstructing this mapping along with a correct class hierarchy is essential for creating a clean call graph. As the Objective-C runtime needs precise information about the class hierarchy to properly resolve method calls, this information must always be contained in the Mach-O file and we can extract it from the file’s sections.

Section __objc_classlist contains a list of pointers to class_t structs, describing the classes contained in the program by their superclass, meta class, size, protocols, methods, instance variables, and properties. Section __objc_class-ref, in contrast, contains a list of classref_t structs describing all classes used by the program at runtime. In the Objective-C runtime (i.e. in Swift and Objective-C likewise), every struct with an isa pointer to a class_t struct is considered a class. The isa pointer indicates the meta-class of the class, i.e. the object providing the methods and properties operating on the class itself – similar to the Class object in Java. Just as every class can have a superclass, every meta-class has a superclass, too. The top of the concrete class hierarchy is indicated by a nil superclass pointer (typically in NSObject), while the top of the meta-class hierarchy is indicated by a cycle, i.e. an isa pointer pointing to the meta-class itself. It is one of Objective-C’s quirks that the topmost meta-class has a superclass pointer to its corresponding concrete class and that accessing the class method of a Class object does not provide its meta-class, but rather the Class object itself. Figure 2 illustrates this possibly at first confusing constellation.

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1. https://github.com/AloneMonkey/frida-ios-dump
Besides classes, the Objective-C runtime supports *protocols*, which are implementation-less and class-independent definitions of methods and properties. Methods declared by a protocol are marked required or optional, and classes adopting the protocol must provide implementations for the former, but may omit any optional method. Protocols support inheritance and classes may adopt any number of protocols. However, in contrast to classes, there is no such thing as meta-protocols – in fact, the Protocol object type extends the base class NSObject. In many cases, the iOS system APIs specify protocols to be implemented by application classes, e.g. to receive data from an API call in a callback function. Thus, knowing the protocols implemented by an app helps reverse engineers understanding the used APIs and functionality of the app. iOS extracts protocol information from the respective Mach-O sections and includes it in the type hierarchy.

Methods of Objective-C classes are identified by *selectors*. Their names are listed as null-terminated strings in section __objc_methname, referenced by a list of pointers in section __objc_selref. As methods are referenced by selectors, rather than direct pointers, the implementation of a method is only loosely coupled to its name and its class, which allows the Objective-C runtime to dynamically manipulate methods (“method swizzling”) and load code. This is great for developers, but a challenge for secure programming and static analysis. As method calls in Objective-C are not implemented as direct BL/BLX branches to specific addresses but rather as a *message* containing the desired object (“IMP”) and method (“SEL”) that is sent to the Objective-C runtime via the **objc_msgSend** function, a naively constructed call graph is almost exclusively centered around that function and does not correctly reflect method calls.

**C. Disassembly**

In parallel to extracting the type hierarchy, we start disassembling the binary starting from each function boundary and then lift disassembled function bodies to a graph representation that can be further processed, as explained in the next section. Besides determining segment boundaries and reconstructing the actual instructions and basic blocks, this includes keeping track of cross-references, e.g. to resolve local variables and the use of constants.

![Fig. 1: Lifting and reverse engineering process](image_url)

![Fig. 2: A class- and meta-class hierarchy](image_url)

**D. Call Graph Reconstruction**

Reconstructing a proper call graph is a prerequisite for any precise interprocedural analysis. Unfortunately, Objective-C has some quirks which make the reconstruction of a call graph not straightforward. As one of the first object oriented languages supporting dynamic binding and message-based dispatching, there is no such concept as a direct method call in Objective-C. Rather, the caller only constructs a message stating a receiver, a selector and optional arguments. This message is handed to the **objc_msgSend** dispatcher of the Objective-C runtime which is responsible for finding the receiver, finding an appropriate method implementation matching the receiver, and performing the call. Thus, when naively creating a call graph from an Objective-C binary, one will receive a construct as shown in 3a. In fact, we are not aware of any disassembly tool (IDA Pro, Hopper, radare2) that is able to construct any other call graph representation than the one shown in 3a. A precise call graph creation requires to reconstruct the possible values of the receiver and selector argument to all **objc_msgSend** calls. As these arguments can be dynamically set at runtime, possibly even by user-provided input values, generally reconstructing them by a static analysis is infeasible. In practice, however, we found...
that reconstruction of these arguments is possible with a high success rate, because the Objective-C/Swift compiler creates selectors as pointers to string constants and receivers as pointers to either the class or object instance. These are typically assigned to registers within the same function as the call to `objc_msgSend`, however not necessarily near the call, nor always constructed in the same way. To reliably reconstruct these argument values, we thus employ the algorithm shown in Algorithm 1 to reconstruct values of the registers `x0` (receiver) and `x1` (selector) for each call to `objc_msgSend`.

### Algorithm 1: Backtracing of registers for method call reconstruction

1. procedure **BACKTRACE**(reg , addr) ▷ reg: register, addr: Code location with use of v
2. V ← {(reg, addr)}
3. while V ≠ ∅ do
4. (x, l) ← pop(V)
5. instr ← INSTRUCTIONATLOCATION(l)
6. if instr is ASSIGNMENT then
7. def ← instr.DEFINITION
8. use ← instr.USE
9. if def matches x then
10. ▷ If immediate pointer to __objc__*-segments:
11. if PointsToConstant(use) then
12. return {DEREFERENCE(use)}
13. else
14. V ← V ∪ {use, l}
15. else if instr is BRANCHINSTR then
16. rcv ← BACKTRACE(x0, pred(l))
17. sel ← BACKTRACE(x1, pred(l))
18. return {rcv, sel}
19. else if pred(l) = ∅ then
20. ▷ If reached begin of function:
21. if x = x0 then
22. ▷ x0 points to own class/instance name
23. return {SELF}
24. else if x = x1 then
25. ▷ x1 points to own function name (selector)
26. return {SEL}
27. else
28. V ← V ∪ {(x, l′) | l′ ∈ pred(l)}

The algorithm operates on a work list `V` holding pairs of registers and code locations. It works backwards along the control flow graph and traces chains of register assignments until it reaches an assignment from a constant or the entry point of the function. The former case is handled by line 12, where registers hold a pointer to some struct in the Objective-C segments (such as __objc_methname). In the latter case, if register `x0` is not explicitly set at all (line 22), it refers to the first parameter of the function, which is typically a pointer to SELF, i.e., the class or object declaring the function. Further, function calls can be constructed dynamically by retrieving receiver and selector as a return value from another function call (line 16). In this case, the algorithm will interprocedurally trace the values by recursively analyzing the called function. Although in theory soundness of the algorithm is limited in that it is only flow- but not path sensitive, our experience is that code created by the Objective-C compiler does not use path-dependent receiver and selector values.

Once receiver and selector have been reconstructed, the aforementioned class hierarchy is looked up to retrieve the address of the actual method implementation and an edge from the caller to that address is inserted into the call graph.

### III. A SUPERGRAPH REPRESENTATION OF LIFTED BINARIES

The information gained during the reverse engineering process must be combined in a single representation serving the analyses. Traditional program analysis frameworks use fixed data structures with strong dependencies which cannot easily be extended and capture only a single level of abstraction (i.e., assembly, object-oriented constructs, or syntactical language-level issues). For most use cases of static source code analysis, this is not a hurdle. For binary analysis, however, we must assume that the individual results of the reverse engineering steps are incomplete, inconsistent, or even missing. We thus choose to merge them in an extensible representation that allows to run analyses on incomplete information at different abstraction levels, obviously sacrificing completeness and – depending on the analysis – also soundness. While this might appear as a drawback to the reader, we point out that soundness and completeness are two extremes that cannot be achieved perfectly at the same time. For analyzing realistic programs, it is much more important to the user that the tool is able to operate on the program at all, while being “as sound and complete as it gets” (cf. [15], [10]).

#### A. Construction of the Supergraph

liOS represents the results of the reverse engineering step in form of a graph representation. The initial graph is constructed from the inputs of the reverse engineering steps (frontends) and subsequently extended by further passes to build a supergraph. This supergraph is the basis for the actual analysis modules, which run graph traversal queries against it. Graph models for static program analysis have been used before [19], [11], [9], however only for approaches operating at source code level and with fixed graph structures. We apply this concept to binary analysis and allow the graph to be extended during analysis. We especially regard the latter aspect as crucial.
TABLE I: Node properties

| Node Label (L) | Property (X) | Description |
|----------------|-------------|-------------|
| PROGRAM        | ea          | Extended address |
|                | name        | Name of binary |
|                | ent32t      | Entitlements of app |
|                | info        | Content of Info.plist |

| FUNCTION       | ea          | Extended address |
|                | name        | Name of function |
|                | is_ext      | External or implemented function |
|                | llvm        | LLVM IR representation of function body |
|                | is_ep       | Is function an entrypoint of the app? |
| METHOD         | name        | Name of method |
| CLASS          | name        | Name of class |
| BASIC BLOCK    | ea          | Extended address |
| INSTRUCTION    | ea          | Extended address |
|                | bytes       | Bytes of the actual instruction |
|                | asm         | Assembly representation |
| IVAR           | ea          | Extended address |

TABLE II: Edges

| Edge                        | Description |
|-----------------------------|-------------|
| impl (FUNCTION × METHOD)    | Method of a class that corresponds to a function |
| succ (BASIC BLOCK × BASIC BLOCK) | Successor of basic block |
| def (INSTRUCTION × INSTRUCTION) | Definition of a variable used by the current instruction |
| implements (FUNCTION × METHOD) | Function implementing a method |
| calls (FUNCTION × FUNCTION) | Function calls (possibly indirect) |
| has superclass (CLASS × CLASS) | Class hierarchy |
| has_protocol (CLASS × PROTOCOL) | Protocols of a class |
| isa (CLASS × CLASS)         | Metaclass hierarchy |
| has meth (CLASS ∪ PROTOCOL) × METHOD | Method of a class/metaclass |

When lifting binaries from assembly to increasingly high-level representations, while coping with possibly incomplete results from each step.

A property graph $PG = (V, E, \Sigma, \sigma, L, \ell)$ is a directed labeled “multi-graph” of vertices $V$ and edges $E = \{(v, u) \in V \times V\}$, where each vertex and edge has a (possibly empty) set of key-value properties. $\Sigma$ denotes an alphabet of property keys for vertices and edges and the property function $\sigma : (V \cup E) \times \Sigma \rightarrow S$ assigns values of value set $S$ to the property keys of vertices and edges. Further, each node and edge is assigned a label by the labeling function $\ell : (V \cup E) \rightarrow L$. The graph can be queried using graph traversal functions. A graph traversal $T = (PG, o, \text{identity})$ is a monoid over a property graph $PG$ with an associative method chaining function $o$ and a neutral element identity. By chaining traversal functions, we can build arbitrary complex queries over nodes and edges and their labels and properties. We write $o^n$ to denote the $n$-times repetition of a traversal function $o$ and denote its reflexive transitive closure. The extensible supergraph comprises different building blocks of an iOS app and as further frontend modules or passes are added to iOS, additional labeled nodes and edges may be added.

The root of the supergraph is a PROGRAM node, representing the Mach-O binary of the app. Its properties hold values such as entitlements and contents from the Info.plist file. PROGRAM has edges to all FUNCTIONS implemented and imported by the binary. Imported external functions have a $\text{is}_\text{EXT}$ property set and an address (EA) of -1, while functions implemented by the application have their function body stored in LLVM IR. While not every function corresponds to a method, the other way round applies: every METHOD of a CLASS that is implemented by the app corresponds to a respective function, denoted by the implements edge. Every function has edges to its basic blocks which have edges to their instructions. These instructions refer to the actual assembly instructions and thus map to specific addresses (EA), as opposed to the LLVM representation. We further capture data flows by adding use-def edges pointing from every use of a memory location or register to the instruction defining its value, whereas the edge is assigned a property $\text{var}$ referring to the respective memory location. Consequently, this basic graph model captures the control flow graph (CFG), call graph (CG), and data dependence graph (DDG), together with additional information such as LLVM IR function bodies and application metadata. Just by processing the graph and without adding further information, this representation allows to construct a forward dominance tree (FDT) and a program dependence graph (PDG), which we do not explicitly compute and store for performance reasons. We will show in the example below in Section V how we can leverage this graph structure to compute static taint flows and data-dependent program slices, i.e. the minimal set of instructions in a function that has equivalent semantics with respect to the values of a specific register or memory location as the original function.

B. Static Program Analysis using the Supergraph

This section discusses the use of graph traversals for building increasingly abstract static analyses in the form of queries against the supergraph. Just like passes can extract the graph to hold more high-level information, we start with basic queries which are then re-used in more complex patterns.

1) Call Graph Traversals: Functions serving as entry points to the application are marked by the boolean property $\text{is}_\text{ep}$. In contrast to traditional Linux binaries, execution of an app does not start at a single main method, but at various callback handlers which must be considered at entry points into the call graph. A graph traversal querying for all vertices with the $\text{is}_\text{ep}$ flag set is rather simple:

$\text{ENTRYPOINTS} = \{v \in V : \sigma(v, \text{is}_\text{entrypoint} = \text{true})\}$

Further exploring the call graph, it will be interesting to find all functions that are called from a given function, i.e. all callees. Considering that function calls in the graph representation already abstract away the specifics of the Objective-C runtime such as reflective invocations via objc_msgSend, this simple graph traversal can already reveal interesting insights into an app, such as the iOS APIs used by it. We denote the
query for all callees of a function $x$ as follows:

$$\text{CALLEES}(x) = \{ v \in V : (x, v) \in E \},$$
$$\ell(v) = \text{FUNCTION},$$
$$\ell((x, v)) = \text{calls}$$

By transitively chaining this graph traversal to get its transitive hull, it is now possible to create a more abstract graph traversal that gives all functions which are transitively reachable from a given function $x$:

$$\text{REACHABLES}(x) = \bigcup_{v \in V} x \circ^* \text{CALLEES}(v)$$

2) Control Flow Traversals: Analog to call graph traversals, the control flow of each function implemented by the app can be explored. For instance, to retrieve all immediate successors of a basic block, i.e. typically the immediately following instruction and the jump target, a graph traversal $\text{SUCCESSORS}$ can be defined.

$$\text{SUCCESSORS}(x) = \{ v \in V : (x, v) \in E \}$$
and
$$\ell((x, v)) = \text{succ}$$

Again, the query for an immediate successor can be transitively extended. Rather than querying for the mere set of all successors (i.e., all blocks of non-dead code in a function), we can retrieve all execution paths from a given basic block $x$. As functions with loops would result in infinite paths, a maximum path length $l_{\text{max}}$ can be set.

$$\text{EXEPATH}(x) = \{ v_0, ..., v_n : v_i, v_{i+1} \in V, (v_i, v_{i+1}) \in E, v_0 = x, n < l_{\text{max}}, \ell((v_i, v_{i+1})) = \text{succ} \}$$

3) Data Flow Traversals: By following the $\text{def}$ edges between instructions in a function, it is further possible to express a backward slicing of a function with respect to a value $q$ used at an instruction $x$:

$$\text{DATAFLOW}(x, q) = \{ v_0, ..., v_n : v_i, v_{i+1} \in V, (v_i, v_{i+1}) \in E, v_0 = x, \sigma((v_0, v_1), \text{var}) = q, \ell((v_i, v_{i+1})) = \text{def} \}$$

### IV. liOS Analysis Framework

In this section, we discuss the software components of liOS and point out how the aforementioned graph traversals can be made more accessible to the user in the form of a simple domain specific language (DSL). liOS uses a plugin-architecture to delegate the graph construction and analysis of liOS to several modules. It first creates an empty graph object and then calls a set of $\text{frontend}$ modules which operate on the binary file and create initial nodes and edges into the graph. liOS then calls a series of $\text{passes}$ – modules which process the existing graph and create further nodes and edges, representing higher-level concepts. Besides extending the graph, passes implement static analyses in the form of graph traversals and optionally make them available as new graph traversals with a shorthand notation in the DSL. That is, a complex graph traversal for an intraprocedural static taint analysis, for instance, can be made available to the user as a simple tainted(source,sink) operation that returns all “tainted” paths from a specific source to a specific sink. The query DSL is implemented on top of the Gremlin\(^3\) graph query language.

#### A. Frontends

Frontends are responsible for extracting information from a binary and provide it in form of a property graph. liOS includes three main frontend modules: the lifter, a disassembly frontend, and a class hierarchy frontend.

1) Lifter Frontend: The lifter operates on the binary and reconstructs the program structure in form of a McSema CFG file\(^4\). As McSema itself is not able to handle specifics of iOS apps, such as cross-references or the class hierarchy, we implemented a new lifter frontend that operates on the aarch64 Mach-O binary, creates the disassembly (using radare2), and reconstructs the control flow graph and cross-references to variables. The result is a McSema-compatible “CFG” file which is then loaded into a graph with nodes representing functions, basic blocks, instructions, variables, and cross-references between code and data locations.

2) Class Hierarchy Frontend: As the lifter is concerned with disassembly only, it does not have any understanding of the object-oriented concepts of Swift and Objective-C. While it merely operates at the level of functions and instructions, we obviously need further information about the class hierarchy which can be easily extracted from the segments of the Mach-O binary. However, none of the existing tools was able to provide a clean and complete representation of the Objective-C class hierarchy to our satisfaction. IDA Pro\(^4\) does not have any understanding of object-oriented structures. jTool dumps only class names. radare2 creates a class hierarchy, but omits properties and protocols. llvm-objdump provides extensive output of the Objective-C segments, but omits the actual pointers to function entry points. We therefore implemented a module to parse the Objective-C sections from the Mach-O file and reconstruct classes, meta-classes, protocols, properties, and methods and add respective vertices and edges to the graph.

3) Disassembly Frontend: The lifter frontend already creates representations of functions, basic blocks and individual instructions. However, it does not parse instructions in any way and only represents them as INSTRUCTION nodes with edges to their basic block. The disassembly frontend adds semantics to instructions by parsing the disassembly using an ANTLR streaming parser\(^3\) and processing the disassembly as follows:

\(^3\)https://github.com/trailofbits/mcsema/blob/master/mcsema/CFG/CFG.proto
\(^4\)version 6.8, in our case
Whenever an instruction refers to a cross-reference, an xref edge to the respective target is inserted into the graph. In case of an immediate operand (i.e., a constant value) or when a direct memory reference to a constant could be reconstructed by radare2, the respective constant value is assigned as a property to the xref’d node. This allows to directly find all uses of a specific constant in the supergraph and is a significant advantage when writing graph traversals.

When an instruction is a branch statement to the objc_msgSend method, we reconstruct the values of the registers holding the SEL and IMP values using the algorithm from Algorithm 1 and insert a call edge into the graph. Direct branches to functions are obviously easier to handle and do not require any back tracing to create a respective calls edge. The output of this frontend is thus comprised of a call graph and cross-references that resemble the actual high-level program in Swift/Objective-C, rather than the immediate references at assembly level.

Further, the disassembly frontend creates use-def edges (named def) connecting the instruction using a memory location to the instructions defining it. As these edges are constructed at assembly level and not in a single static assignment form, a single use instruction may point to several def instructions in different basic blocks. As for memory locations, we support the 31 general purpose ARM registers, as well as references to memory locations, including simple pointer arithmetic on stack-relative offsets.

B. Passes

After creating the initial graph from the frontend’s output, passes are responsible for extending the graph by further edges, nodes, and properties. Although passes are thought of as a plugin-mechanism to add further graph transformations at a later time, liOS includes a built-in pass to link and extend the isolated sub-graphs from the three frontends. For instance, the lifter frontend detects function entries by looking up the values from the LC_FUNCTION_STARTS Mach-O header and gets its name by demangling the respective symbol. The class hierarchy frontend running in parallel takes a different approach and extracts method names from the respective binary segments. As these are more precise in that they do not require demangling and contain the actual method signature, we link functions to methods with a matching address by inserting implements edges between the respective nodes. This way, it becomes possible to query the graph for the precise method signature and retrieve the body of the function implementing the method – either as McSema LLVM IR or as a subgraph of assembly instructions.

C. Extensible Graph Query Language

As a persistence layer, liOS uses the Neo4J graph database [18]. However, to abstract away the persistence layer, liOS does not directly access Neo4J, nor uses its built-in query language ‘Cypher’. Rather, we use the Apache Tinkerpop framework that is a generic graph database interface and allows to easily exchange the backend e.g. by an in-memory database. Tinkerpop also comes with a database-independent graph traversal query language called Gremlin. To make the supergraph more accessible for static analyses, liOS makes use of Gremlin’s support for the creation of domain-specific languages (DSL). The purpose of the DSL is to wrap commonly used traversals in reusable shorthand notations that can be used to build increasingly complex queries. Consider for instance a graph traversal that returns all functions of an application which dynamically load and execute code. In plain gremlin, this query would be written as follows:

```
g.V().hasLabel("FUNCTION")  // Get all functions
.out("has_bb")              // and their basic blocks
.out("instr")               // and their instructions
.out("calls")               // which implement a call
.has("name", "NSInvoke.invoke") // to [NSInvoke.invoke]
```

In liOS’s domain-specific language, the query can be written much simpler by calling the predefined shortcuts functions referring to all functions nodes and filtering them by the calling() shortcut:

```
funs().calling("NSInvoke.invoke")
```

To extend the DSL is such way, pass modules need to provide the implementation of a Gremlin GraphTraversalSource and a GraphTraversal object. The user can then write queries using the DSL and load it into the Jython-based interpreter of liOS.

V. SPOTTING VULNERABILITIES IN IOS APPS

In the following, we illustrate how liOS identifies vulnerabilities in iOS applications. For the sake of demonstration, we consider a remote code execution vulnerability in a JavaScript-Objective-C bridge – a common technique mainly used by advertisement and analytics frameworks such as Google Analytics or MoPub, as well as web-based cross-platform development frameworks such as Apache Cordova or React Native.

A. Example: Vulnerable WebView Delegates

iOS apps use WebView components to render web contents such as HTML, JavaScript, and CSS from the Internet or from local resources in order to display advertisements or refer the user to online web pages without leaving the app. Cross-platform app development frameworks rely to a large extend on WebViews to render HTML-based user interfaces and use native APIs only to access lower-level functionality of the device. This is however not straightforward because web pages are confined in their WebView and cannot make direct calls into the iOS APIs. Although Apple does not provide an official way to provide iOS API access to JavaScript running in a WebView, there is a well-established workaround which is heavily used by applications throughout the app store (approx. 70% of 4000 analyzed apps). It requires registering a delegate object of type UIWebViewDelegate at a WebView
and implementing its method `shouldStartLoadWithRequest` which is invoked by the WebView whenever a new resource is about to be loaded from a URL. Its successor `decidePolicyForNavigationAction` works likewise, and the vulnerability discussed herein is equally applicable.

The function receives the URL as an argument, can perform any action and finally return `YES` or `NO` to determine whether the WebView should load the new URL or discard the request. This can be used to call native functions from a WebView, by encoding the to-be-called functions in the URL, as illustrated by this line of JavaScript:

```javascript
window.location="native:MYCLASS:do_something:param1:param2";
```

By default, the WebView would try to load the URL `native:MYCLASS:do_something:param1:param2` and obviously fail due to the unsupported URL scheme `native:`. To actually call native APIs, the app developer hooks into the WebView’s lifecycle by implementing `shouldStartLoadWithRequest`, parsing the called URL, and mapping it to any native API calls. How this mapping is done remains up to the developer and is cause of a severe vulnerability if done incorrectly. If the implementation directly maps non-sanitized URL parameters to function calls, the app will call any native function as determined by the web page. In combination with either missing or flawed TLS communication or cross-site scripting vulnerabilities in the rendered web page, this opens a remote code execution vulnerability that allows an attacker to inject code into context of the running app and exfiltrate sensitive information from the device. Given the wide-spread use of this technique and the fact that apps can still opt out of transport security (ATS) (done in approx 75% of 4000 analyzed apps), this is a realistic scenario.

Consider the implementation of `shouldStartLoadWithRequest` given in Listing 1.

**Listing 1: Vulnerable WebView delegate**

```objective-c
- (BOOL)webView:(UIWebView *)webView shouldStartLoadWithRequest:(NSURLRequest *)request navigationType:(UIWebViewNavigationType)navigationType
```
pink statement nodes to the head of the shouldStart-LoadWithRequest method. This chain represents the un-sanitized data flow from the method’s argument to the critical NSClassForName call, spanning two basic blocks (created by the if-statement in line 4 of Listing 1) and four calls to external functions before it enters the sink: URL, absoluteString, componentsSeparatedByString, and objectAtIndex. None of these functions is considered to sanitize the argument, so we end up with a critical function that directly operates on possibly malicious user input. The calls invoked by line 8 and 11 of the listing are not contained in the subgraph, because they are not part of the data flow relevant to reach NSClassFromString and thus not part of the program slicing. Retrieving information about the ATS configuration of the application is trivial and can be done by evaluating the info property of the PROGRAM node. As the example shows, liOS is able to detect fairly complex vulnerability patterns that include data flow- and control flow-based program slicings, call graph patterns and configurations from metadata such as from Info.plist. This goes well beyond detecting simple calls to unsafe APIs or incorrectly ordered cryptographic operations.

B. Performance and Footprint

Similar to PQL [11], our approach separates the heavy lifting phase from the actual search for vulnerability patterns. This has the advantage that the computing-intense binary lifting and graph construction needs to run only once, while users may add further analyses at any time afterwards, and simply run them as queries against the already existing supergraph. However, we obviously had to achieve a trade-off between an extensive but slow pre-computation and a faster but limited supergraph creation. To give the reader an impression of performance and memory footprint of liOS, we consider the vulnerable Swift app from above.

The aarch64 Mach-O binary of the app itself is 301 KB large, implements six classes and a total of 85 functions – a large portion of them being stubs and parts of the Objective-C runtime. Additionally, it makes use of 55 external functions which will result in further nodes and edges in the supergraph. Running liOS against the app results in a graph of 6800 nodes, 7340 edges and 13700 property values, totaling to a 5.4 MB graph database. The time to lift the binary amounts to 20 seconds, plus 24 seconds to construct the supergraph and run the passes. It is reasonable to assume that this simple app denotes an upper bound for the ratio of graph database size to binary size and a lower bound for the total database size and computing time.

VI. RELATED WORK

Considerably less work on static analysis of iOS apps than on Android apps exists and as discussed in [12], analyzing binaries imposes significantly higher challenges than source- or bytecode. Nevertheless, the problem has been tackled before by PiOS [5], a privacy analysis approach for iOS binaries by Egele et al., which – similar to our work – strives for an automated reverse engineering and data flow analysis of iOS apps. Also, work by Feichtner et al. [6] aims at identifying vulnerabilities in iOS binaries. Both differ in several aspects from liOS: PiOS hardcodes their data flow analysis directly on 32-bit ARM assembly and does thus not support newer platforms or an extension by vulnerability patterns. Feichtner et al. use dagger, a fork of the LLVM disassembler to lift ARM assembly to LLVM IR and immediately compute a forward program slicing with respect to the use of cryptographic functions. The result is a LLVM slice which is not executable and specific to the analyzed C Crypto API, but typically much smaller than the overall graph generated by liOS. In contrast to these works, liOS combines the result of different reverse engineering inputs, including disassembly and LLVM lifting, into a unified graph representation that tolerates missing information. For LLVM lifting, we extend McSema which in general aims at generating executable bytecode. Rather than detecting a specific vulnerability, liOS thus provides a generic iOS analysis framework that detects vulnerabilities specified by high-level queries. Further, related work includes iRis, an approach describing the reconstruction of Objective-C methods calls to detect the use of private APIs [2] and Cricket [8], a decompiler framework for Objective-C. The difficulty of analyzing a large corpus of realistic iOS apps has been addressed by CRiOS [13], a framework for mass downloading and decrypting apps from the App Store, which achieved a success rate of -51%.

VII. CONCLUSION

With liOS, we push forward the state of the art in static analysis frameworks for iOS apps. To overcome failing and incomplete lifting results, we do not rely on one specific intermediate representation but rather propose an extensible graph-based representation that is populated from various reverse engineering frontends. This representation tolerates missing information and allows static analyses in the form of graph traversal queries. In addition to the overall approach we made practical contributions such as the implementation of a radare2-based disassembly frontend for iOS binaries that fixes various shortcomings of existing lifters. By means of a simple data flow based vulnerability, we illustrated how liOS detects even complex vulnerability patterns using graph traversals. Part of our future work will be to increase soundness of our analysis by investigating the modeling of context-sensitive flows and moving away from generic graph databases to a performance-optimized graph model.

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Fig. 4: Supergraph of a vulnerable data flow. Instructions (pink), basic blocks (blue), functions (green), methods (red), classes (gray), and protocols (yellow)

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