AutoWeb: Automatically Inferring Web Framework Semantics via Configuration Mutation

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***Abstract*—Web frameworks play an important role in modern web applications, providing a wide range of configurations to streamline the development process. However, the intricate semantics, facilitated by framework configurations, present substantial challenges when conducting static analyses on web applications. To mitigate this issue, existing approaches resort to manually modeling framework semantics for static analysis tools. Unfortunately, these manual works are both time-consuming and error-prone, given the multitude of web frameworks and their frequent updates.**

In this paper, we introduce the first automated method for inferring web framework semantics. Our approach automatically deduces framework specifications by mutating configurations. We have developed a prototype tool called AutoWeb and performed extensive experiments on three popular Java web frameworks. Empirical results demonstrate that AutoWeb is comparable to those manual approaches in terms of precision, obtaining a false negative rate of 8.2% with no false positives.

***Index Terms*—static analysis, framework modeling, web framework, Java**

I. Introduction

Modern web applications are commonly built on top of web frameworks. Those frameworks (e.g., Spring [1] and Spring Boot [2]) offer high-level abstractions for common web tasks, thereby greatly simplifying the development process. For instance, many frameworks provide concepts such as *controllers* in the popular model-view-controller (MVC) design pattern: developers can simply declare handler methods for a particular URL without knowing the intricate request dispatching mechanism, and the framework is responsible for processing incoming requests and dispatch them to corresponding handlers.

To effectively analyze web applications, it is crucial to precisely model the semantics of their underlying frameworks, representing the possible frameworks behaviors at runtime. Otherwise, many existing static analyses become inapplicable. For instance, web applications are driven by frameworks to interact with user requests, and there is no `main` method to start with. Furthermore, existing static analyses often fail to capture the dynamically introduced points-to relations and call relations that arise from dependence injection and dynamic dispatching mechanisms within frameworks, resulting in unsound and imprecise results. Unfortunately, frameworks are notoriously hard to analyze statically. They often employ hard-to-analyze dynamic patterns (implemented via reflection) to interact with application code, and their concrete semantics are customized by the application via configuration files or annotations. It is a daunting task, if not impossible, to automatically analyze frameworks with good precision.

In practice, researchers resort to manually modeling framework semantics to analyze web applications. Framework features were embedded as hard-coded elements in the analysis implementation [3], [4], [5]. In addition, researchers proposed various more general solutions to specify framework semantics, effectively modeling behaviors in given configurations [6], [7]. For instance, IBM's F4F [6] defined the Web Application Framework Language (WAFL) to express framework-related behaviors of web applications, where WAFL specifications are generated by hand-crafted generators (one for each framework). JackEE [7] declares framework-related behaviors using Datalog rules, effectively mapping framework configurations to static relations, which can be processed by the Doop [8] analysis engine. Nevertheless, those existing approaches still need manual efforts and can be labor-intensive and error-prone, particularly when frameworks undergo frequent updates.

This paper presents an automatic method for inferring web framework semantics. To the best of our knowledge, this is the first approach of such an attempt. Since it is generally infeasible to directly deduce the concrete semantics by analyzing the complex implementation details of web frameworks, we do not consider framework-specific concepts such as *filters* and *controllers*. Instead, we focus our analysis on the relations between application objects or methods, which are framework-introduced but commonly required by static analyses, i.e., entry points, points-to relations, and call relations.[1] Previous work [9], [10] has also shown that the above relations are crucial for the static analysis of web applications. Web frameworks offer rich semantics that are configured with hundreds of different parameters, and our goal is to automatically deduce the semantics under given configurations, i.e., demystifying

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[1]Techniques described in this paper are applicable to infer other user-defined relations.

how entry methods and call/points-to relations are introduced by frameworks using particular configuration parameters. The framework semantics are abstracted as mappings from configuration parameter sets to relation types, referred to as *specification* in this paper. Specifications are framework-related, yet application-independent, and can be applied to specific applications to model framework semantics.

Based on the observation that a framework-introduced relation is declared by the *minimal sufficient and necessary set* (MSNS) to trigger the relation, which is the set of minimum relation-triggering configuration parameters, we propose a *mutation-based approach* to identifying the MSNS for each relation. Specifically, given an application program construct P with framework-introduced relation R, our approach first identifies the *necessary* condition of relation R by removing configuration parameters from P until R cannot be triggered at runtime. Then, new configuration parameters (mutated from identified necessary conditions) are introduced to further verify that the set of necessary configuration parameters is *sufficient* to trigger relation R.

We develop a prototype tool, AUTOWEB, to demonstrate the effectiveness of our approach. AUTOWEB observes framework-introduced relations during execution, then mutates configuration parameters to identify the MSNS for a relation. We have experimented with AUTOWEB on three popular Java web application frameworks, namely Servlet, Spring, and Apache Struts2. Experimental results demonstrated that AUTOWEB can automatically generate specifications as precise as the state-of-the-art manual approaches. To summarize, this paper makes the following contributions:

- We propose the first automated method to infer web framework semantics, by identifying the MSNS for framework-introduced relations.
- We develop AUTOWEB, utilizing a novel mutation-based approach to automatically deduce the framework specifications.
- We experimented AUTOWEB on three popular Java web frameworks, and experimental results demonstrated that the inferred specifications are comparable with hand-written specifications over precision and soundness.

The rest of the paper is organized as follows. Section II motivates our approach with an example, and Section III describes AUTOWEB in detail. We evaluate the tool AUTOWEB in Section IV. Section V reviews related work and Section VI concludes this paper.

II. MOTIVATION

In this section, we aim to introduce the dynamic relations facilitated by web frameworks, illustrating their impact on static analysis through an example.

A. Motivating Example

Figure 1 gives an example application built on top of the Spring framework. The execution flows for two URLs are illustrated in Figure 2. In this example, a SQL injection vulnerability exists at line 49. This vulnerability

```
1  @Controller
2  public class Controller1 {
3      @Autowired
4      @Qualifier("service2")
5      ServiceInterface srv;
6
7      @GetMapping("/root1/path1")
8      public String handle1(HttpServletRequest request){
9          ...
10         data = request.getParameter("name");
11         srv.service(data);
12         ...
13     }
14 }
15
16 @Controller
17 @RequestMapping("/root2")
18 public class Controller2 {
19     @RequestMapping("/path2")
20     public String handle2(HttpServletRequest request){
21         ...
22         data = request.getParameter("name");
23         sql = "update users set hit=hit+1 where
           ↪   name='"+data+"'";
24         statement.executeUpdate(sql);
25         ...
26     }
27 }
28
29 public class Filter1 extends OncePerRequestFilter{
30     protected void doFilterInternal(HttpServletRequest
       ↪   request, HttpServletResponse response,
       ↪   FilterChain chain){
31         if(validateSqlCharactor(request)) // Santitizer
32             chain.doFilter(request, response);
33         ...
34     }
35 }
36
37 @Service("service1")
38 public class ServiceImpl1 implements  ServiceInterface{
39     public String service(String name) {
40         // safe SQL operation
41         ...}
42 }
43
44 @Service("service2")
45 public class ServiceImpl2 implements ServiceInterface{
46     public String service(String name) {
47         ...
48         String sql = "select * from users where
           ↪   name='"+name+"'";
49         stmt.executeQuery(sql); // SQL injection
50         ...}
51 }
```

(a) Application code.

```
1  <!--web.xml configuration file-->
2  <web-app>
3      <filter>
4          <filter-name> myFilter </filter-name>
5          <filter-class> Filter1 </filter-class>
6      </filter>
7      <filter-mapping>
8          <filter-name> myFilter </filter-name>
9          <url-pattern> /root2/* </url-pattern>
10     </filter-mapping>
11 </web-app>
```

(b) XML configuration file. “myFilter” is the alias of the class “Filter1” in Figure 1a.

Fig. 1: Motivating example of a Spring-based application.

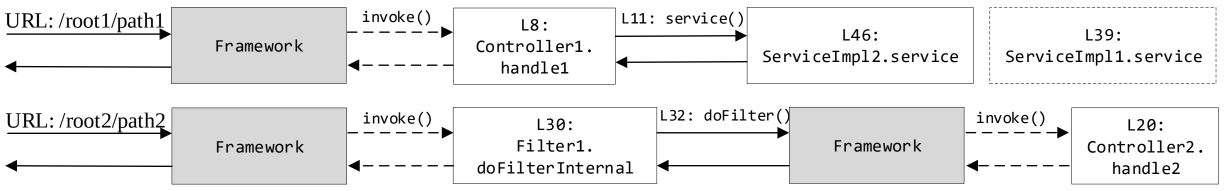


Fig. 2: Execution flow of the example in Figure 1. Solid lines indicate direct call edges, while dotted lines denote indirect calls. The content above the solid line represents the callsite, with the line number appearing to the left of the colon.

occurs because `Controller1.handle1()`(line 11) invokes `ServiceImpl2.service()` (line 46), which directly passes input data to a SQL query (line 49). Note that `Controller2.handle2` (line 20) also passes input data to SQL query statements (line 24). However, it is considered safe since the input request is sanitized by `Filter1` at line 31, before being processed by the handler.

The SQL injection in the above example can be detected via a classical taint analysis which computes whether the parameters of SQL queries are input data without being sanitized or not. However, without awareness of framework-introduced relations, traditional static taint analyses often fail to recognize the execution flow as in Figure 2, resulting in ineffective analysis results.

B. Framework-introduced Relations

1) Entry Points: Static analysis including taint analysis typically process on a call graph consisting of all reachable methods from *entry points*. In standalone Java applications, the `main` method is considered the entry point, whereas in web applications, entry points are often the request-handling methods directly invoked by frameworks. `Controller1.handle1()` and `Filter1.doFilterInternal()` are entry points in our example.

Entry points are defined by annotating classes and methods via Java annotations or XML configurations. As shown in Figure 1a, the annotation `@Controller` defines entry classes, and the annotation `@GetMapping` and `@RequestMapping` declare entry methods. Note that the annotation `@GetMapping` and `@RequestMapping` also have parameter values to specify corresponding request URLs. Additionally, entry points can also be declared via XML configurations as shown in Figure 1b.

2) Points-to Relation: Points-to relations denote the set of heap objects referred by a pointer variable. Similar to call relations, points-to relations can be dynamically introduced by frameworks: frameworks can create objects outside the application and inject their managed objects into particular field references. In our example, an object of type `ServiceImpl2` is managed by the framework and injected into field reference `Controller1.srv`. Such framework-introduced points-to relations cannot be computed by existing points-to analyses. Consequently, a call graph algorithm based on points-to analysis will miss the call relation from line 11 to `ServiceImpl2.service()`, resulting in false negatives. On the other hand, a CHA-based call graph construction algorithm will introduce a spurious call relation to `ServiceImpl1.service()`, resulting in false positives.

Points-to relations are specified by annotating fields and classes of injected objects. In our example, field `Controller1.srv` is annotated with `@Autowired` (line 3) and `@Qualifier` (line 4), indicating that the field is injected with framework-managed object `service2`. The `@Service` annotation at line 37 and 44 suggest that object `service1` and `service2` are managed by the framework, with type `ServiceImpl1` and `ServiceImpl2`, respectively. Note that the parameter value of `@Qualifier` matches with that of `@Service`, indicating that object `service2` is injected into field `Controller1.srv`.

3) Call Relation: Call relations can be statically computed using techniques such as class hierarchy analysis (CHA) [11] or points-to analysis [12], to establish connections between invocation sites and corresponding callee methods. Nevertheless, these analyses are unable to handle indirect call relations introduced by frameworks. In such cases, applications invoke framework APIs, which, in turn, call back into application methods, making it challenging for static analysis techniques to accurately track and resolve these dynamic interactions.

Indirect call relations can be specified in various ways. In our example, the method `Controller2.handle2()` is indirectly called by `chain.doFilter()` at line 32 because it handles the URL `/root2/path2` which matches with the URL `/root2/*` in the XML configuration for filter-mapping (Figure 1b).

Objective. The framework-introduced relations mentioned above are specific because they are tied to a particular application. Our objective is to automatically extract the general framework semantics (e.g., the annotations, `@Controller` and `@GetMapping`, together specify an entry method), which can be leveraged by a static analysis tool to analyze a wide range of applications that use similar annotations. Alternatively, we can manually produce specifications for frameworks, one by one. Nonetheless, such manual work can be error-prone and labor-intensive.

III. Methodology

We present AutoWeb to infer framework-introduced relations for given configurations. The key idea of AutoWeb is to automatically identify the minimal sufficient and necessary set (MSNS) for a relation by mutating configurations. In practice, AutoWeb can run on a set of sample applications to generate framework specifications and the generated specifications can be used in analyzing other web applications.

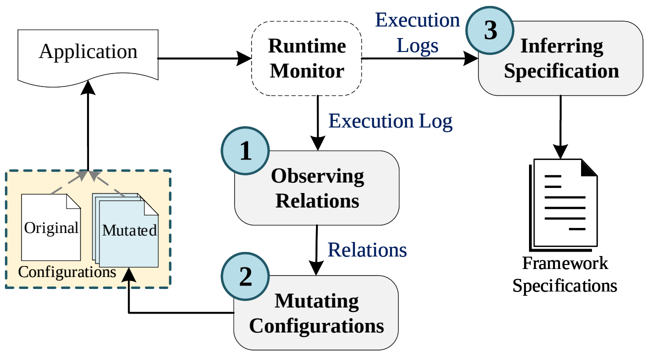


Fig. 3: Overview of AutoWeb. Black solid lines depict the workflow, while gray dotted lines indicate a singular choice.

Figure 3 overviews AutoWeb. The input is a runnable web application, and we partition it into two distinct logical modules: configurations and others in the input application.

1) The input application is firstly instrumented and traced to acquire the initial execution log using the original configurations. This step aims to observe relations including entry points and call/points-to relations.
2) Mutated configurations are generated by removing or adding configuration parameters from the original configurations. The MSNS for each relation can be identified by comparing the dynamic relations of different mutations. The application runs using mutated configurations in this step.
3) Finally, the concrete relation and configuration parameters are symbolized to generate specifications that map each relation type to the configuration set.

Next, we will elaborate on each step using the example in Figure 1.

A. Observing Relations

This step aims to collect the concrete framework-introduced relations from the initial execution information. In the Runtime Monitor component, Javaassist [13], [14], [15] is employed to instrument the input application, modifying its Java bytecode before class loading. To capture entry point/call relations, we insert logging statements before and after each method call, as well as at the entry and exit of each method. We log field read statements for points-to relations. Additionally, the entry and exit of the request handling methods of web containers (e.g., *Apache Tomcat* [16]) are also logged to track coming requests. These request sequences will later be used to interact with mutated applications.

```
1   ㉘[Req]/root1/path1
2   ㉘[mtd]Controller1.handle1(...)
3   ...
4   ㉘[fieldRead]Controller1.srv:ServiceImpl2
5   ㉘[callsite]line:11
6   ㉘[mtd]ServiceImpl2.service(...)
7   ...
8   ㉘[mtdEnd]ServiceImpl2.service(...)
9   ㉘[returnSite]line:11
10  ㉘[mtdEnd]Controller1.handle1(...)
11  ㉘[ReqEnd]/root1/path1
12  ㉗[Req]/root2/path2
13  ㉗[mtd]Filter1.doFilterInternal(...)
14  ...
15  ㉗[callsite]line:32
16  ㉗[mtd]Controller2.handle2(...)
17  ...
18  ㉗[mtdEnd]Controller2.handle2(...)
19  ㉗[returnSite]line:32
20  ㉗[mtdEnd]Filter1.doFilterInternal(...)
21  ㉗[ReqEnd]/root2/path2
```

Listing 1: Simplified runtime logs of the example in Figure 1.

As web applications handle multiple user requests concurrently, each log statement includes its thread identifier. Relations including entry methods and call/points-to relations can be easily deduced from execution logs within the same thread, as follows.

$Rule_{entry}$: Method m is an entry method if there is a log instance "[mtd] m" immediately following "[Req]".
$Rule_{call}$: Method m is called directly or indirectly at call site c if there is a log instance "[mtd] m" immediately following "[callsite] c".
$Rule_{ptsto}$: Field f references to an object of type t if there is a log instance "[fieldRead] f t".

Listing 1 shows the simplified execution logs of our motivating example. The logs are grouped by thread id ㉘ and ㉗, triggered by the coming request "/root1/path1" (line 1–11) and ends with the log instance "/root2/path2" (line 12–21), respectively.

The execution logs precisely capture all triggered relations. To focus solely on relations introduced by the framework, we exclude relations that can already be computed by existing static analyses. In Listing 1, line 2 and line 13 confirm that `Controller1.handle1` and `Filter1.doFilterInternal` are entry methods ($Rule_{entry}$). Lines 15–16 suggest that `Controller2.handle2` is indirectly invoked at line 32 of application code in Figure 1 by the invocation `doFilter` ($Rule_{call}$). Line 4 states that field `Controller1.srv` refers to an object of type `ServiceImpl2` ($Rule_{ptsto}$). Column 2 in Table I shows the set of concrete relations.

B. Mutating Configurations

After step 1, we observed the set of dynamically triggered concrete relations. Given a framework-introduced relation R, we try to identify the MSNS $\mathcal{S}$ for R, i.e., the minimum set of configuration parameters triggering R. To this end, we mutate configuration parameters based on the following guidelines.

TABLE I: Observed relations and corresponding configurations.

Relation Type	**Concrete Relation** R	**Minimal Sufficient and Necessary Set** $\mathcal{S}$
Entry point	*entry* : `Controller1.handle1`	{`@Controller`$\prod$`Controller1`, `@GetMapping`$\prod$`handle1`}
	entry : `Filter1.doFilterInternal`	{`@filter`$\prod$`Filter1`,`Filter1`$\trianglelefteq \ldots$, `doFilterInternal`$\trianglelefteq \ldots$}
Points-to	`Controller1.srv:ServiceImpl2`	{`@Autowired`$\prod$`srv`, `@Qualifier`$\prod$`srv`, `@Service`$\prod$`ServiceImpl2`}
Call relation	`32:Controller2.handle2`	{`API:doFilter`, $C_{32}/m_{32} \trianglelefteq \ldots$, `@filter`$\prod C_{32}$, $\mathcal{S}\prod${`Controller2`,`handle2`} }

Necessity: Configuration parameter C is a necessary condition of R, i.e., $C \in \mathcal{S}$, if the resulting effect of removing C is that R is not triggered, while other relations remain unaffected.
Sufficiency: The configuration set $\mathcal{S}$ is sufficient to trigger R, if a mutated configuration set $\mathcal{S}'$ can trigger a correspondingly mutated relation R'.

Hence, our approach firstly identifies necessary conditions for relation R by removing each configuration parameter one by one until R cannot be triggered. Next, the set of necessary conditions is mutated to further verify whether it is sufficient to trigger a correspondingly mutated relation R'.

In processing relation R, we only need to consider configurations related to R, which is the set of Java annotations or XML attributes attached to related program constructs of R. Hereafter, we use the notation $\mathcal{S}\prod p$ to denote configurations $\mathcal{S}$ on program construct p. Entry point relation $entry : C.m$ involves configurations $\mathcal{S}\prod\{C, m\}$, where $C.m$ represents the entry method m inside class C; points-to relation $f : C$ relates to configurations $\mathcal{S}\prod\{f, C\}$, where f and C are the field and its type respectively; and Call relation $c : C.m$, denoting that method m inside class C is invoked at callsite c, involves configurations $\mathcal{S}\prod\{c, C_c, m_c, C, m\}$, where C_c and m_c refer to the containing class and containing method of callsite c, respectively. The types of configuration parameters include Java annotations and XML configuration files. In addition, we also consider extensions of framework APIs including sub-typing and method overriding as special configurations, denoted by the notation $\trianglelefteq$.

TABLE II: Mutation strategy.

original relation	mutated relation
$\mathcal{S}\prod\{C, m\} \implies entry : C.m$	$\mathcal{S}\prod\{C', m'\} \implies entry : C'.m'$
$\mathcal{S}\prod\{f, C\} \implies f : C$	$\mathcal{S}\prod\{f', C'\} \implies f' : C'$
$\mathcal{S}\prod\{c, C_c, m_c, C, m\}$ $\implies c : C.m$	$\mathcal{S}\prod\{c', C_{c'}, m_{c'}, C', m'\}$ $\implies c' : C'.m'$

Table II presents the mutation strategy to verify sufficient conditions. In summary, original program constructs p related to relation R are duplicated and renamed to p'. Configurations $\mathcal{S}$ on p are moved to the mutated construct p' instead. Each mutation action generates a *mutated configuration set*, which is used to replace original configurations and then executed to verify whether a correspondingly mutated relation R' on p' can be triggered or not.

Next, we elaborate on how the MSNS for distinct relations are identified for our motivating example. The result for each observed relation is shown in Column 3 of Table I.

a) Entry point: In Figure 1, `Controller1.handle1` and `Filter1.doFilterInternal` are entry points. Let us consider the concrete relation *entry* : `Controller1.handle1`. There are two related configuration parameters `@Controller`$\prod$`Controller1` and `@GetMapping`$\prod$`handle1`. Both parameters are necessary since the relation cannot be triggered after removing either of them. Furthermore, a new relation *entry* : `Controller1'.handle1'` can be triggered by applying our mutation strategy in Table II. As a result, we have identified the MSNS {`@Controller`$\prod$`Controller1`, `@GetMapping`$\prod$`handle1`} for this concrete relation. The entry method `Filter1.doFilterInternal` involves the XML configuration on class `Filter1` (`filter`$\prod$Filter1) and two additional configurations derived from API extension, sub-typing from `OncePerRequestFilter` (`Filter1`$\trianglelefteq \ldots$) and overriding of method `doFilterInternal` (`doFilterInternal`$\trianglelefteq \ldots$), which form the MSNS for this relation.

b) Points-to relation: We observe a points-to relation `srv:ServiceImpl2` in our motivating example. There are three related configuration parameters: `@Autowired`$\prod$`srv`, `@Qualifier`$\prod$`srv`, and `@Service`$\prod$`ServiceImpl2`. Removing either annotation will disable the points-to relation.

To mutate the set of configurations, we introduce a new class `ServiceImpl2'` and a new field `srv'`, duplicated from `ServiceImpl` and `srv`, respectively. Next, the set of configurations is removed from the original program constructs and applied to the newly duplicated field and class instead. In another word, the configuration set $\mathcal{S}\prod${`srv`, `ServiceImpl2`} is mutated to another set $\mathcal{S}\prod${`srv'`, `ServiceImpl2'`}. The mutated application will trigger the points-to relation `srv':ServiceImpl2'`. Hence, the three configuration parameters consist of the minimal sufficient and necessary set for the points-to relation `srv:ServiceImpl2`.

c) Call relation: Call relation preserves the semantics of indirectly invoking application methods via framework API. That is, application invokes framework APIs, which in turn, call back into application methods. For this, we consider configuration parameters on the callsite (including its containing class and method), as well as configuration parameters on the invoked method (including its containing class).

For concrete call relation `32:Controller2.handle2` in our example, the callsite (line 32 in Figure 1) is constrained with the following configurations: line 32 invokes API `doFilter` (`API:doFilter`), m_{32} derived from `doFilterInternal` ($m_{32} \trianglelefteq \ldots$, C_{32} (class `Filter1`) derived from `OncePerRequestFilter` ($C_{32} \trianglelefteq \ldots$), and C_{32} configured as `filter` in XML (`filter` $\prod C_{32}$). These configurations, together with configurations on the invoking method ($\mathcal{S}\prod$ {`Controller2`, `handle2`}) are the corresponding minimal sufficient and necessary set.

TABLE III: Inferred Specifications of the motivating example shown in Figure 1.

Relation type	**Relation** R	**Specification** (content for relation type)
Entry point	$entry : C.m$	$\{$`@Controller`$\prod C$, `@GetMapping`$\prod m\ \}$ $\{$`@filter` $\prod C$, $C \trianglelefteq$ `OncePerRequestFilter`, $m \trianglelefteq$ `doFilterInternal` $\}$
Points-to	$f : C$	$\{$`@Autowired`$\prod f$, `@Qualifier`$(S_1)\prod f$, `@Service`$(S_2)\prod C$, $S_1 \sim S_2\}$
Call relation	$c : C.m$	$\{$`API:doFilter`, `@filter` $\prod C_c$, $C/m \trianglelefteq \ldots$, `@Controller` $\prod C$, `@RequestMapping` $\prod m\ \}$

C. *Inferring Specifications*

Until this point, we have obtained a set of relations with their corresponding minimal sufficient and necessary sets. However, the relations and configurations are concrete: they are tied to concrete program constructs and the value (if any) of a configuration parameter is a constant string. In this step, we generalize the relation R and its corresponding configurations to abstract program constructs, according to the following rule.

Generalization: Concrete application program constructs (classes, methods, and fields) are generalized to abstract program constructs. The constant string parameters of a configuration are generalized to a symbolic string with constraints matching the string to the name of a program construct, or to the parameter of another configuration. Symbolic strings with no matching constraints can be discarded.

Table III summarizes the specifications inferred from our example in Figure 1. The specifications look similar to the minimal sufficient and necessary set for a concrete relation, with concrete program constructs and constant configuration parameters symbolized.

As shown in Table III, we have inferred two rules for entry point relation. The first rule states that the two configurations `@Controller`$\prod C$ and `@GetMapping`$\prod m$ collectively declare that $C.m$ is an entry method, regardless of their parameters. The second rule indicates that method $C.m$ is an entry method if $C.m$ extends from `OncePerRequestFilter.doFilterInternal` and C is configured as a filter by `@filter`$\prod C$. Note that in this rule, we only generalize application classes and methods while preserving concrete framework constructs. In the third rule, points-to relation $f : C$ holds under the following conditions: f is annotated with `@Autowired` and `@Qualifier`(S_1), C is annotated with `@Service`(S_2), and the two symbolic string parameter S_1 and S_2 match with each other ($S_1 \sim S_2$). Here S_1 and S_2 are parameters of configuration `@Qualifier` and `@Service`, respectively. The last rule indicates that if c invokes API `doFilter` in a method derived from `doFilterInternal` ($C/m \trianglelefteq \ldots$), it may indirectly invoke $C.m$ if $C.m$ is a request handler (`@Controller` $\prod C$, `@RequestMapping` $\prod m$) and C_c is a filter (`@filter` $\prod C_c$) with parameter matching the name of C ($S \sim C.name$).

a) Limitations: Points-to/Call relation connects a field-/callsite to corresponding class/methods. The connection between distinct program constructs are often indicated by their configuration parameters, where the parameter may match with another parameter or with the name of a program construct. For the points-to relation `srv:ServiceImpl2` in our example, the parameter of configuration `@Qualifer("service2")` on field `srv` matches with the parameter of configuration `@Service("service2")` on class `ServiceImpl2`.

However, it is often challenging to statically determine whether a parameter matches another due to the flexibility provided by frameworks. Parameters can be configured using options such as regular expressions or string manipulation operations. For instance, the call relation `32:Controller2.handle2` happens because the URL processed by the containing class of line 32 (class `MyFilter`) matches with the URL handled by `Controller2.handle2`. However, the URL processed by `MyFilter` is configured as a regular expression `/root/*`. Moreover, we need to join parameters of the two configurations `@RequestMapping(/root2)` and `@RequestMapping(/path2)` together to construct the URL handled by method `Controller.handle2`. It is rather challenging to recognize the above intricate connection automatically, and our approach will discard the matching constraints between the two URL parameters.

IV. Evaluation

A. *Experimental Setup*

Implementation We implemented a prototype that includes all the components as depicted in Figure 3, and took the benchmarks as inputs to generate framework specifications. Additionally, we employed the specifications crafted by AutoWeb within JackEE, a web application analysis engine on top of Doop [8] for static program scrutiny.

Platform. The experiments of inferring framework specifications were conducted on an Intel Core(TM) i5-4590 (3.3GHz) laptop with 32 GB of RAM, running the Windows 10 Professional version.

Benchmarks. We experimented AutoWeb on three popular web application frameworks: *Servlet* [33], *Spring*(including *Spring* [1] and *Spring-boot* [2]), and *Apache Struts2* [34]. Our experimental benchmarks comprise two parts.

- The 16 open-source web applications listed in Table IV encompass diverse open platforms, founded on any of the three aforementioned frameworks, various application categories (such as blogging systems and e-shops), and star ratings. This benchmark spans a variety of applications, blending both popular and less-known ones, complex and straightforward structures.
- The 8 web applications from JackEE, which are suggested by experts or top-popularity representatives of major classes of enterprise applications. One is free-binary-only, and the others are open-source.

TABLE IV: Details of collected open-source benchmarks and runtime information.

ID	Benchmark	Properties					Instrument	Mutation		Inferring
		Application Classes	Total Classes	Stars	Forks	Frameworks	Log Size(M)	Mutation Number	Run Success %	Recall %
1	community [17]	94	19544	2.3k	739	Servlet, Spring	47.6	167	86.75%	90.00%
2	halo [18]	425	45359	22.1k	7.5k	Servlet, Spring	12.5	398	69.41%	94.44%
3	iCloud [19]	22	9498	183	115	Servlet, Spring, Struts2	0.5	242	96.61%	100.00%
4	jpetstore [20]	24	6847	521	745	Servlet, Spring	36.6	104	98.08%	100.00%
5	logicaldoc [21]	2013	51494	61	31	Servlet, Spring	122	780	62.50%	100.00%
6	LMS [22]	33	14329	420	187	Servlet, Spring, Struts2	0.5	213	84.13%	100.00%
7	B2CWeb [23]	41	17434	481	343	Servlet, Spring, Struts2	0.8	155	82.96%	100.00%
8	newbee-mall [24]	89	13463	9.4k	2.5k	Servlet, Spring	172	117	76.92%	100.00%
9	NewsSystem [25]	66	20065	19	8	Servlet, Spring, Struts2	158	93	76.92%	60.00%
10	openkm [26]	2968	88843	527	255	Servlet, Spring	207	421	98.05%	100.00%
11	RuoYi [27]	290	38320	3k	1k	Servlet, Spring	2.79	310	75.28%	92.31%
12	showcase [28]	42	8937	5k	3.8k	Servlet, Spring	1.4	695	78.71%	100.00%
13	petclinic [29]	24	29092	395	1.8k	Servlet, Spring	1.75	337	75.00%	100.00%
14	WebApp [30]	75	28722	1.3k	610	Servlet, Spring	1.56	290	80.07%	100.00%
15	struts-examples [31]	170	13507	405	543	Servlet, Struts2	11.2	1022	98.33%	100.00%
16	Struts2-Vuln [32]	20	4569	170	38	Servlet, Struts2	0.3	176	99.43%	100.00%

Columns 2–7 are the details of benchmark properties. Columns 8–11 show the details of runtime information. The rest of the figures and tables of this paper would use "ID" to represent each benchmark instead of benchmark names. Benchmarks **struts-examples** and **Struts2-Vuln** are two collections that contain 41 and 16 micro-benchmarks, respectively.

Our experiments aims to answer the following research questions:

RQ1 Can our approach automatically infer framework-introduced semantics of web applications?
RQ2 How precise are the inferred specifications?
RQ3 How is the quality of generated specifications compared to manually written ones?

B. RQ 1: Feasibility

a) AutoWeb: AutoWeb offers an automated and user-friendly solution that minimizes the need for manual setup throughout the workflow. Human involvement is solely required during the initial phase, primarily to interact with the deployed applications, which can be streamlined through using tools like [35]. Then, AutoWeb automates the following steps leveraging information directly derived from the initial actions. Compared to human learning, which involves static analysis and framework knowledge, the cost is notably lower. While resources like StackOverflow [36] and official documentation facilitate rapid initiation, they often lack insights into the correlation between framework usage and static analysis semantics. Establishing these connections requires intricate, labor-intensive manual intervention, making it a challenging and time-consuming endeavor.

The applications in Table IV are used as the input of AutoWeb to generate specifications. The runtime information of AutoWeb is detailed in Columns 8–11 in Table IV. The size of execution log produced by each application using the original configurations, is outlined in Column 8. Column 9 displays the number of mutated configuration sets generated by AutoWeb. Each mutation concerns one configuration for one relation. Column 10 denotes the success rate of application execution using these mutated configurations. Apart from benchmarks 2 and 5, all other benchmarks achieved success rates exceeding 75% during execution. Even in benchmarks 2 and 5, a significant number of successful runs amounted to 277 and 488, respectively. The final column in Table IV presents the recall ($TP/(TP + FN)$), demonstrating that all benchmarks, except benchmark 9 (to be discussed in IV-C), achieved recall rates surpassing 90%. The extensibility of AutoWeb lies in two aspects, namely new frameworks and new relation types. New frameworks are already supported by AutoWeb (discussed shortly), while certain components need to be enhanced to support new relation types.

TABLE V: Detailed results of inferred specifications.

ID	Configurations Number			Entry		Inject		Call	
	All	Reach.*	Spec.*	FN	FP	FN	FP	FN	FP
1	19	15	9	**1**	0	0	0	0	0
2	80	60	17	0	0	0	0	**1**	0
3	6	6	4	0	0	0	0	0	0
4	6	6	2	0	0	0	0	0	0
5	18	9	9	0	0	0	0	0	0
6	8	7	6	0	0	0	0	0	0
7	7	4	4	0	0	0	0	0	0
8	19	14	8	0	0	0	0	0	0
9	9	9	3	0	0	0	0	**2**	0
10	67	30	5	0	0	0	0	0	0
11	59	27	12	0	0	**1**	0	0	0
12	29	28	12	0	0	0	0	0	0
13	33	31	10	0	0	0	0	0	0
14	34	19	7	0	0	0	0	0	0
15	29	16	8	0	0	0	0	0	0
16	3	3	2	0	0	0	0	0	0

Reach. denotes reachable configurations at runtime.
Spec. represents specifications inferred by AutoWeb (Section III-C)

b) Specification: The benchmarks encompass a total of 152 configuration parameters: 60 for classes, 39 for methods, and 53 for fields. Among these configuration parameters, 121 are specific to the three frameworks under manual investigation, while the remaining parameters are associated with other frameworks utilized within the applications, such as Stripes [37]. Additional details regarding the count of distinct configuration parameters in each benchmark can be found in columns 2 to 4 of Table V.

The specifications derived from the 16 benchmarks en-

TABLE VI: Part of inferred entry-point (EP) specifications.

Line	Class	Method
EP1	@RestController	@PostMapping
EP2	beans->bean[class]	beans->bean[destroy-method]
EP3	-	@Action
EP4	struts->package->action[class]	struts->package->action[method]
EP5	web-app->filter->filter-class	Filter.doFilter(...)
EP6	-	@DefaultHandler

The "-" symbol represents any configuration.

compass 96 entry point types, 9 points-to types, and 17 indirect call types. These specifications involve configuration parameters for 17 classes, 20 methods, 10 fields, as well as 46 additional sub-types within the framework API. To enhance understanding and application of these specifications, we provide an excerpt of inferred entry point relations. Both points-to and call relations exhibit similarities.

Table VI displays some of the results regarding entry point types in the specifications. Each row indicates that when a method and its associated class satisfy the specified configuration parameters, the method becomes an entry point, and the class becomes the entry class. EP 1, 3, and 6 correspond to annotation configurations, while EP 2, 4, and 5 are associated with XML configurations. In the case of EP6, the method also needs to override the designated method. The results shown are divided by frameworks: EP 1–2, EP 3–4, EP 5, and EP 6 belong to frameworks Spring, Struts2, Servlet, and Strips [37], respectively. It is worth mentioning that initially, we did not consider Strips but AUTOWEB still inferred the corresponding specification (EP 6), confirming our approach can be generalized to other new frameworks.

Since specifications are generalized and not specific to any application, they can be utilized by existing static analyzers to analyze any web application built on the frameworks outlined in the specifications. After that, static analyzers can understand framework semantics to facilitate various analyses, such as call graph construction [12], and information analysis [38].

Conclusion. To sum up, our proposed technique is feasible in practice: AUTOWEB can automatically generate precise framework specifications, saving heavy human effort. Moreover, AUTOWEB is readily applicable to other frameworks (e.g., Stripes) and relation types, confirming the generality of our approach.

C. RQ 2: Specification Accuracy

The specifications generated by AUTOWEB should exhibit minimal or zero false positives to prevent any adverse impacts when used directly in static analysis. To this end, we manually verify the accuracy of all inferred specifications by examining the source code, with a summary of the results provided in Table V. During the verification process, we focus on the following two issues:

- **False Positives.** Are there any incorrectly inferred relations that contradict framework semantics?
- **False Negatives.** Are there any correct relations that were not inferred but were observed during runtime?

a) False Positives: Table V (Columns 6, 8, 10) reveals no false positives in any of the benchmarks. This is due to the specifications being inferred from runtime information, which is subsequently verified by the actual execution of the application. As a result, AUTOWEB effectively avoids false positives, ensuring the correctness of the framework semantics introduced in the static analysis.

b) False Negatives: There are only five false negatives for all benchmarks. These false negatives are hidden behind certain factors during runtime, preventing them from being apparent. One factor is embedding the configuration content directly in the code, rendering the configuration on the code(annotations or XML files) ineffective. For example, in the `community` project, removing the parameter "`@RequestMapping`" does not take effect at runtime because the application has a default response function that produces the same result as the configuration parameter. Another factor is the language feature. For example, in `RuoYi`, the false negative for the field-inject relation is related to the "`@Value`" annotation. This occurs because all fields annotated with this configuration are Java primitive types, which always have default values. Moreover, complex string configurations lead to false negatives. In the `NewsSystem`, a false negative is caused by intricate string manipulation. Specifically, the configuration `<action name="AdminAction_*" method="1">` utilizes the implicit configuration value "{1}" to represent the method name, relying on the incoming URLs. Another false negative arises from multi-layer references in XML attributes, which are not yet supported.

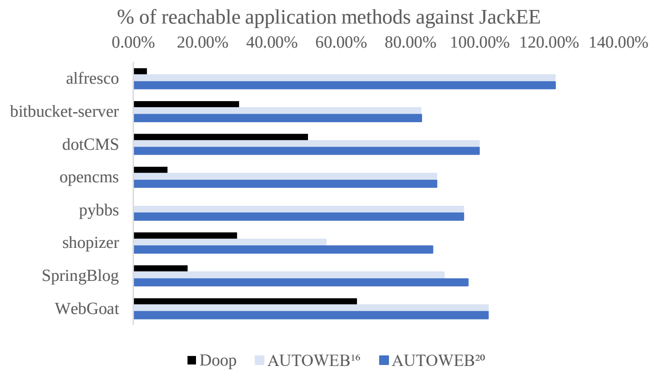
Note that false negatives in one application may appear as true positives in other applications. For instance, the Entry-point relation `@RequestMapping` is FN in `community` appears as true positive in `newbee-mall`. More input projects would bring more complete specifications, which will be discussed in IV-D. The average false negative rate summarized from all inferred specifications is 8.2%.

Conclusion. Upon analysis, we identified that the false negatives in our inferred specifications were a consequence of configurations outside the scope of our analysis. Importantly, the inferred specifications exhibit no false positives, indicating their direct applicability as framework knowledge for static analysis tools.

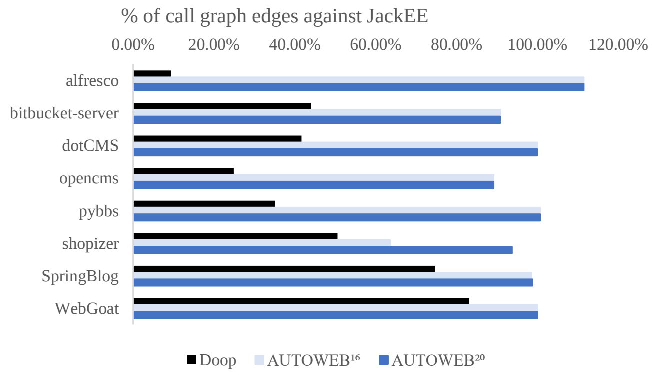
D. RQ 3: Comparison with Existing Work

The state-of-the-art tool, JackEE [7], offers open-source specifications across various web frameworks. JackEE is built on top of Doop [8], which is a collection of various analyses expressed in the form of Datalog [39] rules, and all the framework specifications are written in Datalog rules. To assess the efficacy of the specifications generated by AUTOWEB, we converted them into Datalog rules, replacing all configuration specifications of JackEE. Taking JackEE's specifications as the baseline, we evaluate specifications produced by AUTOWEB as well as the default specifications from Doop.

a) Comparison Dimension: Framework knowledge helps static analyses to better understand the application behaviors. To evaluate the quality of specifications, we focus on *reachable application methods* and *call graph edges*.



(a) Application methods reachability against JackEE.



(b) Call graph edges against JackEE.

Fig. 4: Reachability for different metrics.

b) Comparison Method: We choose JackEE (with its manual specifications) as the baseline. Doop also provides its own handwritten specifications, and we include them for completeness. We considered 8 benchmarks from JackEE (mentioned in IV-A) for evaluation. Among these benchmarks, 1 entails a prolonged setup duration, 2 encounter deployment problems, and 1 is not open-sourced. As a result, we use 4 benchmarks to enrich the specifications generated by AUTOWEB. Hence, we have two sets of specifications: (1) AUTOWEB^{16} contains the specifications generated using 16 benchmarks in Table IV-A. (2) AUTOWEB^{20} denotes the enriched specifications using 20 (16 + 4) benchmarks.

c) Result: Figure 4a and Figure 4b compare Doop, AUTOWEB^{16}, and AUTOWEB^{20} against JackEE on reachable (application) methods and call graph edges, respectively. When comparing AUTOWEB^{16} with JackEE, the ratios range from 83.14% to 121.73% on reachable methods, averaging 96.59%; For call graph edges, the numbers vary from 89.18% to 111.48%, averaging 98.09%. Moreover, AUTOWEB^{16} significantly outperformed Doop. On the other hand, AUTOWEB^{20} exhibited improvements over AUTOWEB^{16}, particularly in benchmarks such as `shopizer` and `SpringBlog`, where previously missing configurations, absent in the initial 16 benchmarks, were later inferred. This underscores that using a more extensive set of inputs can lead to richer specifications, as discussed in section IV-C0b. Furthermore, our specifications include correct configuration parameters that may have been overlooked manually. For example, we identified annotations like `@PostMapping` and `@ExceptionHandler` as entry-point relations, while JackEE did not recognize them. This highlights the presence of unsystematic and incomplete issues of manually configured specifications.

Conclusion. Concerning the quality of constructed call graphs, the specifications inferred by AUTOWEB are comparable with those manual ones in JackEE. Furthermore, our approach excels at identifying overlooked configuration parameters during manual writing.

V. RELATED WORK

The related work encompasses two main areas: modeling framework behaviors, and automatic summarizing of program semantics.

a) Modeling Framework Behaviors: As mentioned in section I, previous works modified each analysis engine with human knowledge on-demand, which suffers from limited reusability. Some studies attempted to develop reusable models for specific frameworks to address this limitation, which still rely on human knowledge. ANTaint [9] needs manually modeled core features of Spring like bean injection and AOP. The Oracle team [40] manually wrote rules to identify entry points only for Java EE Servlet applications. CGNCG [41], [42], F4F [6], [43], and JackEE [7] all need human effort to obtain knowledge of the framework and static analysis. Static Analysis Refining Language (SARL) [44] can also obtain framework-introduced relations via iterative software analysis. However, the analyzer also needs to point out and add the missing framework knowledge. Unlike AUTOWEB, all these approaches rely on the knowledge of frameworks and static analysis, and require extra manual effort for new frameworks.

b) Automatic Summarizing Program Semantics: Research on exploiting automatic approaches to summarizing framework library specifications used in static analysis [45], [46], [47] became more popular. These approaches mined information flow specifications with additional running information over libraries, rather than writing them by hand. However, the purpose of these approaches is to summarize the framework library APIs' semantics, especially for Android, not to deal with complex but frequently used configurations (e.g., XML files). Therefore, these approaches do not apply to web applications that mostly use non-code configurations.

VI. CONCLUSION

Web applications heavily rely on web frameworks, making it imperative to precisely model framework semantics for static analysis. In this paper, we proposed the first automated method to produce specifications that encode general framework semantics. To that end, we identify the minimal necessary and sufficient set for a framework-related relation by mutating configurations. Experimental results on three mainstream Java frameworks demonstrate that our technique is comparable to existing state-of-the-art manual approaches, obtaining a marginal 8.2% false negatives with no false positives.

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