Instrumenting Microservices for Concurrent Audit Logging: Beyond Horn Clauses

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***Abstract*—Instrumenting legacy code is an effective approach to enforce security policies. Formal correctness of this approach in the realm of audit logging relies on semantic frameworks that leverage information algebra to model and compare the information content of the generated audits logs and the program at runtime. Previous work has demonstrated the applicability of instrumentation techniques in the enforcement of audit logging policies for systems with microservices architecture. However, the specified policies suffer from the limited expressivity power as they are confined to Horn clauses being directly used in logic programming engines. In this paper, we explore audit logging specifications that go beyond Horn clauses in certain aspects, and the ways in which these specifications are automatically enforced in microservices. In particular, we explore an instrumentation tool that rewrites Java-based microservices according to a JSON specification of audit logging requirements, where these logging requirements are not limited to Horn clauses. The rewritten set of microservices are then automatically enabled to generate audit logs that are shown to be formally correct.**

***Index Terms*—Audit logs, concurrent systems, microservices, programming languages, security**

I. Introduction

Audit logging is a prevalent mechanism used by applications to capture the runtime events for the purpose of post-facto analysis, user accountability, diagnostics, security in-depth, etc. In this regard, enabling systems to generate necessary and sufficient logs plays a crucial role to meet the goals of audit logging. However, inadequate audit logging has been recognized as common problem in software development [**?**], [1]. While the audit log inadequacy problem can be solved by naively recording massive volume of information at runtime, this approach incurs inefficiency in performance and response to different security incidents [3]. For example, industrial control systems may suffer from the lack of monitoring audit logs in realtime to identify the security breaches [**?**]. Correctness of audit logging ensures to only record the necessary information.

Information-algebraic [4] models have been used within the last decade to provide semantic frameworks for audit logging. This has been accomplished by interpreting audit logs as well as the runtime structure of processes as information-algebraic elements, intuitively reflecting on their information content [**?**]. Correct audit logging relies on this algebraic interpretation by comparing the information content of audit logs vs. program at runtime. Using this semantic framework, an implementation model has been proposed for linear processes that ensures correct audit logging, leveraging program instrumentation techniques [5]. The same framework has also been employed to identify and analyze direct information flows in Java-like settings [**?**], [**?**]. This semantic framework has also inspired the study of audit logging correctness in concurrent systems [6], which facilitates to log an event if one or more trigger events have occurred on the same or other concurrent components. The audit logging requirements can be specified with Horn clauses, where each event is a call to a function in a concurrent component, associated with its contextual information, e.g., the time of occurrence.

Using microservices has become a popular approach in application development in recent years, and many organizations report success in its adoption [**?**]. Some surveys show more than 70% of partial or full adoption worldwide in recent years [**?**]. In this approach, a system is decomposed into multiple standalone loosely-coupled components, called microservices. Each microservice has its own database, and can run on a separate machine, VM, or container. Microservices commonly communicate with each other by sending messages through RESTful APIs. The accommodated modularity by a microservices-based system provides better maintainability which results in improved security, feature updates, and the ability to continue operating (at least partially) despite the failure of one or more components. Microservices-based applications are architecturally concurrent and thus are good candidates to study the effectiveness of the aforementioned framework for audit logging in concurrent environments.

Using the implementation model for audit logging in concurrent systems [6], in a previous work [**?**] we have described an instrumentation tool for Java microservices that are built on Spring framework. The tool supports audit logging requirements that can be specified by Horn clauses, according to which the instrumentation tool modifies different microservices so that concurrent audit logging is supported by the whole system. To accomplish this, the instrumented services may contact a Prolog engine to communicate the Horn clause specification of the logging requirements as well as the trigger and logging events. The Prolog engine is used to deduce whether logging in a certain microservices must take place.

In this paper, we go beyond Horn clauses to specify audit

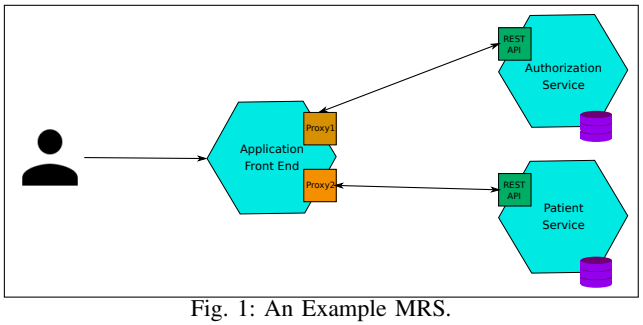


Fig. 1: An Example MRS.

logging requirement and study a sequel to the instrumentation tool, mentioned above, where we can use a more expressive class of audit logging requirements to specify the conditions upon which logging must happen. The formal implementation model of correct audit logging in concurrent systems with the extended audit logging requirements is described in [**?**]. Our proposed tool for Java microservices relies on this implementation model. Since audit logging requirements are extended beyond Horn clauses our tool cannot simply communicate the logging requirements directly to a Prolog engine. We propose an algorithm through which Prolog is used to deduce intermediary candidate events to be logged and filter out the ones that do not satisfy logging preconditions.

In the following, we describe an illustrative example that demonstrates the need to go beyond Horn clauses to specify audit logging requirements.

Example: Microservices-based medical records system. Let's consider a medical records system (MRS) with microservices architecture. Among numerous services that such system includes, this example assumes the existence of at least the following: 1) A front-end service that authenticates the users and multiplexes their queries to the back-end services, 2) an authorization system that controls access to system resources, and 3) a patient services that manages patient information. Figure 1 demonstrates these microservices in a high-level manner. One common authorization-related operation in healthcare systems is to "break-the-glass" [8] in critical scenarios, which refers to accessing certain information (e.g., patient medical history) without any mediating authorization checks. After a user breaks the glass, actions of that user is recorded in the log for a posteriori analysis and establish user accountability. A first attempt to specify the policy could be *"Store in the log all accesses to patient medical history by a user who has already broken the glass"*. This policy can be specified in Horn clause logic, and for which previous work proposes an implementation model [6] and a tool for Java-based microservices [**?**].

However, the aforementioned policy entails to log all such accesses indefinitely. In reality, breaking the glass is deactivated once the critical situation is resolved. Therefore, we may consider some dual capability "mend-the-glass" that restores access control and enforces it fully, if the glass is already broken. Having this capability, the example break-the-glass policy can be restated as follows: *"Store in the log all accesses to patient medical history by a user who has already broken the glass and has not mended it afterwards"*. This updated more realistic specification goes beyond Horn clauses in expressivity.

Therefore, a compelling next step is to consider a more powerful instrumentation tool to implements logging specifications that support extended preconditions like the one discussed above. Our instrumentation tool relies on implementation models of correct audit logging which support more expressive classes of logging specifications.

Paper outline. The rest of the paper is organized as follows. In Section II, we review the formal implementation model, discussing an instrumentation algorithm for systems in π-calculus. In Section III, we discuss our tool to instrument microservices in Java Spring. In addition, we present a demo of a microservices-based MRS, and its instrumentation by our tool. Related work is discussed in Section IV. Finally, Section V concludes the paper.

II. A Brief Review of the Instrumentation Model

In [**?**], we have explored the full formalization of the implementation model for instrumenting concurrent systems that guarantee the correctness of audit logs, according to logging specifications that go beyond Horn clauses. In this section, we review this model briefly.

A. Source System Model

The source system Π is concurrent program, which is modeled in π-calculus [9]. Top-level components of Π, denoted by A, are called top-level agents. Top-level agents execute in parallel, and communicate among themselves as their functionality dictates. Some A consists of internal modules and/or functions, modeled as subagents B^A. As part of the definition of the source system, we assume the existence of a codebases $\mathcal{C}_\mathcal{U}$ and $\mathcal{C}_\mathcal{L}$ that include definitions of the form $A(x_1, \cdots, x_n) \triangleq \cdots$ and $B^A(x_1, \cdots, x_n) \triangleq \cdots$ resp.

B. A Class of Logging Specifications

Horn clause logic has been used to specify audit logging requirements in previous work [**?**], where certain events must take place so that audit logs are generated. In this paper, we go beyond Horn clauses in our implementation model to help specify not only the necessity of having certain events to occur, but also to ensure that another group of events do not take place. In this respect, we define a class of specifications that assert temporal relations among the events that must or must not transpire in different components (top-level agents) of the system. Using this extended class of specifications, a particular event must be logged, provided that a certain set of events have taken place and another set of events have not. We would call these different sets of events positive and negative triggers, resp. We use $Spec_{log}$ to denote this class of specifications. In $Spec_{log}$, each event is modeled as a sub-agent invocation, i.e., a module within one of the agents of the system. Figure 2 depicts the structure of specifications in $Spec_{log}$. $\mathrm{Call}(t, A, B, mathitxs)$ asserts the event of invoking sub-agent B^A at time t with list of parameters xs. ϕ and ψ_j

$$\forall t_0, \cdots, t_n, xs_0, \cdots, xs_n \,.\, \mathrm{Call}(t_0, A_0, B_0, xs_0) \bigwedge_{i=1}^{n} (\mathrm{Call}(t_i, A_i, B_i, xs_i) \wedge t_i < t_0) \wedge \varphi(t_0, \cdots, t_n) \wedge \varphi'(xs_0, \cdots, xs_n) \bigwedge_{j=1}^{m} (\forall t'_j, ys_j \,.\, \psi_j(xs_0, \cdots, xs_n, ys_j) \wedge \psi'_j(t_0, \cdots, t_n, t'_j) \implies \neg\mathrm{Call}(t'_j, A'_j, B'_j, ys_j)) \implies \mathrm{LoggedCall}(A_0, B_0, xs_0)$$

Fig. 2: $Spec_{log}$ clause structure.

$$\mathcal{C}_{\mathcal{L}}(\texttt{Authorization})(\texttt{breakTheGlass}) = [\texttt{breakTheGlass}^{\texttt{Authorization}} \triangleq P] \text{ for some } P$$

$$\mathcal{C}_{\mathcal{L}}(\texttt{Authorization})(\texttt{mendTheGlass}) = [\texttt{mendTheGlass}^{\texttt{Authorization}} \triangleq P'] \text{ for some } P'$$

$$\mathcal{C}_{\mathcal{L}}(\texttt{Patient})(\texttt{getMedicalHistory}) = [\texttt{getMedicalHistory}^{\texttt{Patient}} \triangleq Q] \text{ for some } Q$$

$$\forall t_0, t_1, p, u \,.\, \mathrm{Call}(t_0, \texttt{Patient}, \texttt{getMedicalHistory}, [p, u]) \wedge \mathrm{Call}(t_1, \texttt{Authorization}, \texttt{breakTheGlass}, [u]) \wedge t_1 < t_0 \wedge (\forall t_2 \,.\, t_2 < t_0 \wedge t_1 < t_2 \implies \neg\mathrm{Call}(t_1, \texttt{Authorization}, \texttt{mendTheGlass}, [u])) \implies \mathrm{LoggedCall}(\texttt{Patient}, \texttt{getMedicalHistory}, [p, u])$$

Fig. 3: Example logging specification for an MRS.

are possibly empty conjunctive sequence of literals of the form $t_i < t_j$. A_0 is called a *logging event agent*, whereas other A_is are called *positive trigger agents*. A'_js are called *negative trigger agents*. Similarly, *logging event sub-agent* refers to B_0, and other B_is are called *positive trigger sub-agents*. B'_js are called *negative trigger sub-agents*. *Logging preconditions* are predicates $\mathrm{Call}(t_i, A_i, B_i, \tilde{x})$ for all $i \in \{1, \cdots, n\}$ and $\mathrm{Call}(t_j, A'_j, B'_j, ys_j)$ for all $j \in \{1, \cdots, m\}$.

For example, in the microservices-based MRS, described in Figure **??**, each microservice, including Authorization and Patient, is a top-level agent in Π. Authorization may include modules to break and mend the glass, and Patient may have a functionality to read patient medical history. These functionalities are defined as part of $\mathcal{C}_{\mathcal{L}}$ (Figure **??**). Moreover, Figure **??** describes the logging specification in $Spec_{log}$ that is associated with the break-the-glass policy. In this clause, t_0 and t_1 are timestamps, and t_1 precedes t_0. p refers to the patient identifier, and u is the user identifier who breaks the glass and attempts to read the medical history of p later on. Additionally, logging is preconditioned on the fact that the glass is not mended in between the events of breaking the glass and gaining access to the patient medical data.

C. Target System Model

The instrumentation algorithm maps a Π system to a target system, denoted by $\Pi_{\log}$ system. Runtime environment of $\Pi_{\log}$ includes a timing counter t, Δ that returns the set of logging preconditions transpired in a given agent, Σ that returns the set of logging preconditions that have transpired the triggers of a given agent, and Λ that stores the audit logs for a given agent. The preconditions in Σ must be communicated between a given agent and all triggers agents. Certain prefixes are added to $\Pi_{\log}$ to facilitate storage and retrieval of information to these runtime components: 1) $\mathsf{callEvent}(A, B, \tilde{x})$ updates $\Delta(A)$ with predicate $\mathrm{Call}(t, A, B, \tilde{x})$, 2) $\mathsf{addPrecond}(x, A)$ updates$\Sigma(A)$ with precondition x, 3) $\mathsf{sendPrecond}(x, A)$ converts $\Delta(A)$ to a transferable object and sends it though link x, and 4) $\mathsf{emit}(A, B, \tilde{x})$ studies the derivability of $\mathrm{LoggedCall}(A, B, \tilde{x})$ and accordingly $\Lambda(A)$ is updated with this predicate.

$$\mathcal{C}'_{\mathcal{L}}(\texttt{Authorization})(\texttt{breakTheGlass}) = [\texttt{breakTheGlass}^{\texttt{Authorization}}(u) \triangleq \mathsf{callEvent}(\texttt{Authorization}, \texttt{breakTheGlass}, [u]).P] \qquad \mathcal{C}'_{\mathcal{L}}(\texttt{Authorization})(\texttt{mendTheGlass}) = [\texttt{mendTheGlass}^{\texttt{Authorization}}(u) \triangleq \mathsf{callEvent}(\texttt{Authorization}, \texttt{mendTheGlass}, [u]).P']$$

$$\mathcal{C}'_{\mathcal{L}}(\texttt{Patient})(\texttt{getMedicalHistory}) = [\texttt{getMedicalHistory}^{\texttt{Patient}}(p, u) \triangleq \mathsf{callEvent}(\texttt{Patient}, \texttt{getMedicalHistory}, [p, u]).c_{\overline{\texttt{PA}}}.c_{\texttt{PA}}(f).\mathsf{addPrecond}(f, \texttt{Patient}).\mathsf{emit}(\texttt{Patient}, \texttt{getMedicalHistory}, [p, u]).Q] \qquad \mathcal{C}'_{\mathcal{L}}(\texttt{Authorization})(D_{\texttt{PA}}) = [D_{\texttt{PA}}^{\texttt{Authorization}}(c_{\texttt{PA}}) \triangleq c_{\texttt{PA}}.\mathsf{sendPrecond}(c_{\texttt{PA}}, \texttt{Authorization}).D_{\texttt{PA}}^{\texttt{Authorization}}(c_{\texttt{PA}})]$$

Fig. 4: Example Instrumentation of the MRS.

D. Instrumentation Algorithm

Given a logging specification in $LS \in Spec_{log}$, algorithm $\mathcal{I}$ translates a Π-system into a $\Pi_{\log}$-system with concurrent audit logging capabilities to support LS. In the following we briefly point out main aspects of how $\mathcal{I}$ works.

If A_i is a logging event agent and A_j is a positive or negative trigger agent, a fresh link c_{ij} is added between them. This link is used to communicate locally transpired trigger events that are stored in trigger agents' Δ component. sendPrecond and addPrecond prefixes are used for this purpose.

$\mathcal{I}$ inserts prefix callEvent before at the starting point of each negative/positive trigger sub-agent. This ensures storing trigger events in Δ.

callEvent is also inserted at the starting point of logging event sub-agents to capture logging events in Δ component of the corresponding agents. In addition, addPrecond is inserted to notify all positive/negative trigger agents to send their trigger events through the established c_{ij} link to the logging event tigger. The received trigger events are then stored in Σ component of the logging event agent. Finally, the logging event must check if the invocation of logging event sub-agent will be logged in Λ. For this purpose, emit is inserted.

Each positive/negative trigger A_j must be able to respond to the requests by some logging event agent A_i on the c_{ij} link. To this end, $\mathcal{I}$ introduces new sub-agent D_{ij} in code base of A_j that indefinitely listens on that link and returns the content of Δ on the same link. This is accomplished by sendPrecond prefix.

As an example, having the definitions in Figure 3 for an MRS, $\mathcal{I}$ modifies the definition of sub-agents `breakTheGlass`$^{\texttt{Authorization}}$, `mendTheGlass`$^{\texttt{Authorization}}$ and `getMedicalHistory`$^{\texttt{Patient}}$ by injecting proper prefixes at their starting points. In addition, a new link $c_{\texttt{PA}}$ is introduced between `Authorization` and `Patient` agents, and a new sub-agent $D_{\texttt{PA}}^{\texttt{Authorization}}$ is added that listens on $c_{\texttt{PA}}$ indefinitely for requests from `Patient` and responds with locally transpired trigger events, i.e., invocations to `breakTheGlass` (positive) and `mendTheGlass` (negative) in this example.

III. Instrumenting Microservices

In this section, we explain the implementation of the instrumentation algorithm for microservices-based applications, as well as a demo of how the tool modifies these applications based on different logging specifications. In our instrumentation tool, each microservice of an application is treated as an agent of the concurrent system, whereas each method defined in some library of a microservice is considered as a sub-agent.

A. Instrumentation Tool: LogInst

We have implemented the proposed algorithm $\mathcal{I}$ for microservices-based applications that are deployed using Java Spring Framework. Our instrumentation tool [**?**], LogInst, receives a logging specification along with an application consisting of two or more microservices, and rewrites those microservices accordingly. LogInst extends microservices with required RESTful APIs that facilitate the communication between microservices for the sake of audit logging.

The logical specification of logging requirements (Section II-B) is passed as an argument to LogInst in JSON format. LogInst parses this JSON file and extracts logging specification in the form of Horn clauses, along with identifying triggers and logging events. The paths to different microservices of the application are also passed to LogInst. LogInst applies modifications to each microservice component according to the logging specification. In addtion, the path to the Prolog engine must be fed to LogInst. LogInst uses SWI Prolog [10] to logically infer the derivation of logging events according to the logging specification, the set of facts regarding trigger events, etc.

LogInst uses aspect-oriented programming (AOP), in particular AspectJ, to weave concurrent logging capability into microservices. For this purpose, LogInst extends the Project Object Model of the microservices which need to be instrumented by spring-boot-starter-aop dependency.

According to the implementation model, the configuration of the concurrent system includes three different structures to store the logging preconditions that are transpired locally (Δ), logging preconditions that are originated remotely (Σ), and the audit logs recorded by an agent (Λ). These structures are added by LogInst as repositories of logical facts that are kept on nonvolatile memory. If a microservice is only a trigger, then a repository is added to that microservice to store logging preconditions that take place locally in that microservice. However, if a microservice is a logging event, then that microservices is extended with all three types of repositories. We call these repositories local-db, remote-db, and log-db, resp. Note that according to the definition of $\mathcal{I}$ (Section II-D), a trigger is only concerned with locally transpired preconditions (through callEvent prefixes), whereas a logging event needs to access all three types of aforementioned structures (through callEvent, addPrecond, and emit prefixes).

$\mathcal{I}$ extends every trigger with sub-agents, D_{ij}, that send back the locally generated preconditions upon receiving a request on a dedicated link (using sendPrecond prefix). LogInst implements this feature by extending each trigger microservice with a REST controller that sends back the content of local-db, if it receives an HTTP GET request on the dedicated path /localdb. This controller is denoted by LocalDBController, henceforth. On the other side, a logging event microservice is supposed to contact the trigger on dedicated links to receive the preconditions that are transpired in trigger agents. LogInst facilitates this by extending every logging event microservice with a web client that sends asynchronous HTTP GET requests to /localdb path on trigger microservices and collects the responses. We have called this service RestClient.

```
@Before("execution (some trigger)")
public void someAspect(JoinPoint){
        ...
        build precondition from JoinPoint
        add precondition to local-db
        ...
}

@Before("execution (some logging event)")
public void someAspect(JoinPoint) {
        ...
        build precondition from JoinPoint
        add precondition to local-db
        ...
        send GET to triggers
        collect the responses in remote-db
        ...
        add logging specification to the engine
        add the content of local-db to the engine
        add the content of remote-db to the engine
        query the engine and update log-db
        ...
}
```

Fig. 5: Pseudocode of *before* advice for triggers and logging events.

As mentioned earlier, AOP is used to add logging capabilities to microservices. For this purpose, LogInst identifies the pointcuts in which an advice needs to be defined. According to $\mathcal{I}$, trigger sub-agents are preceded by callEvent prefixes. For this purpose, LogInst defines *before* aspects for each of the trigger methods, where the advice includes the construction of preconditions from the join points and adding them to local-db. This implements the semantics of callEvent.

$\mathcal{I}$ instruments logging event sub-agents by inserting a sequence of operations before the execution of these sub-agents. This sequence includes callEvent prefixes, communication on dedicated links to receive remotely transpired logging preconditions, adding them to Σ using addPrecond prefixes, and finally checking if logging events should to be logged, using emit. LogInst handles this by defining *before* aspects for the pointcuts that correspond to logging event methods. Similar to the aspects defined for trigger methods, the advice for logging event methods starts with the construction of preconditions from join points and adding them to local-db. Next, RestClient is used to asynchronously send an HTTP GET request on the predefined path /localdb to each of the trigger microservices, and collect the results in remote-db. This implements the semantics of addPrecond prefix. Then, SWI Prolog engine is invoked to add the logging specification, and the contents of local-db and remote-db. Finally, the Prolog engine is queried to study if the invocation of logging event must be logged, and accordingly log-db repository is updated. These final steps implement the semantics of emit prefix. In order to facilitate the communication between SWI Prolog engine and Java Virtual Machine, InterProlog Java/Prolog SDK [11] is used.

Figure 5 specifies the advice for triggers and logging events in general form. Figure 7a depicts some of the aforementioned modifications that LogInst applies architecturally to the logging event and trigger microservices.

B. Case Study: Instrumenting MRS_{Demo} with LogInst

In Section I, we discussed an oversimplified MRS consisting of several loosely-coupled microservices. We have

implemented [**?**] a demo of this system, $\texttt{MRS}_{\texttt{Demo}}$, consisting of several microservices, using Java Spring Boot [12]. The front-end microservice of $\texttt{MRS}_{\texttt{Demo}}$ authenticates users and acts as the API gateway by relaying requests to the back-end microservices.

In the following, we explain how $\texttt{MRS}_{\texttt{Demo}}$ is instrumented by `LogInst` for a given logging specification. In Figure 3, we have described a logging specification that enforces logging access to patient medical history at any point after breaking the glass. We can assert a similar logging specification rule in JSON [**?**] , which is more verbose than its logical equivalent. `LogInst` parses that JSON specification and constructs the Horn clause given in Figure 6 (ver. 1), which is then added to SWI Prolog engine fact base. Note that in this Horn clause presentation, we have redacted the full package names of the trigger and logging event methods and replaced them with `<package>`, for the sake of space economy. `LogInst` instruments $\texttt{MRS}_{\texttt{Demo}}$ according to this logging specification rule as follows: `spring-boot-starter-aop` dependency is added to the POM of Patient and Authorization services. Authorization service is extended with `local-db`. Patient service is extended with `local-db`, as well as `remote-db`, and `log-db`. Authorization service is extended with the REST controller `LocalDBController` that responds to requests on path `/localdb`. Patient service is extended with `RestClient` web client. A *before* aspect is added to Authorization service with `AuthorizationController.breakTheGlass` as its pointcut. This aspect builds preconditions from the join point and appends them to `local-db`. A *before* aspect is added to Patient service with pointcut `PatientController.getPatientMedHistByName`, to 1) build preconditions from the join point and append them to `local-db`, 2) send HTTP GET request on path `/localdb` to Authorization service, and store the results in `remote-db` repository, 3) add the logging specification, and contents of `local-db` and `remote-db` repositories to the SWI Prolog engine, and 4) send queries to the Prolog engine to check derivability of `loggedfunccall` predicates and accordingly update `log-db` with the engine's response.

These changes describe the real-world instrumentation of the MRS, formally given in Figure 4. Note that Authentication microservice is unaffected when instrumented by `LogInst`, as it does not include any trigger or logging event methods according to the logging specification.

The two other versions (Figure 6) are example extensions to the policy ver. 1 . In ver. 2, authenication is considered as an additional trigger. Therefore, in addition to the aforementioned changes, `LogInst` extends Authentication microservice with `local-db` repository, `LocalDBController`, and a *before* aspect (trigger version). The *before* aspect of Patient microservice is also extended with sending HTTP GET requests to Authentication microservice on path `/localdb`, and storing the results in `remote-db`. In ver. 3, two additional triggers are considered in Authorization and Patient microservices. `LogInst` applies the same changes given above, along with

```
/* Version 1 */
loggedfunccall(T0, patient-service,
  "<package>.PatientController.getPatientMedHistByName", [U, P]) :-
 funccall(T0, patient-service,
  "<package>.PatientController.getPatientMedHistByName", [U, P]),
 funccall(T1, authorization-service,
  "<package>.AuthorizationController.breakTheGlass", [U]),
 <(T1, T0), ==(U, user).

/* Version 2 */
loggedfunccall(T0, patient-service,
  "<package>.PatientController.getPatientMedHistByName", [U, P]) :-
 funccall(T0, patient-service,
  "<package>.PatientController.getPatientMedHistByName", [U, P]),
 funccall(T1, authorization-service,
  "<package>.AuthorizationController.breakTheGlass", [U]),
 funccall(T2, authentication-service,
  "<package>.AuthenticationService.authenticate", [U]),
 <(T1, T0), <(T2, T1), ==(U, user).

/* Version 3 */
loggedfunccall(T0, patient-service,
  "<package>.PatientController.getPatientMedHistByName", [U, P]) :-
 funccall(T0, patient-service,
  "<package>.PatientController.getPatientMedHistByName", [U, P]),
 funccall(T1, authorization-service,
  "<package>.AuthorizationController.breakTheGlass", [U]),
 funccall(T2, patient-service,
  "<package>.PatientController.getAllPatients", [U]),
 funccall(T3, authorization-service,
  "<package>.AuthorizationController.getBTGUsers", []),
  <(T1, T0), <(T2, T0), <(T3, T0), ==(U, user).
```

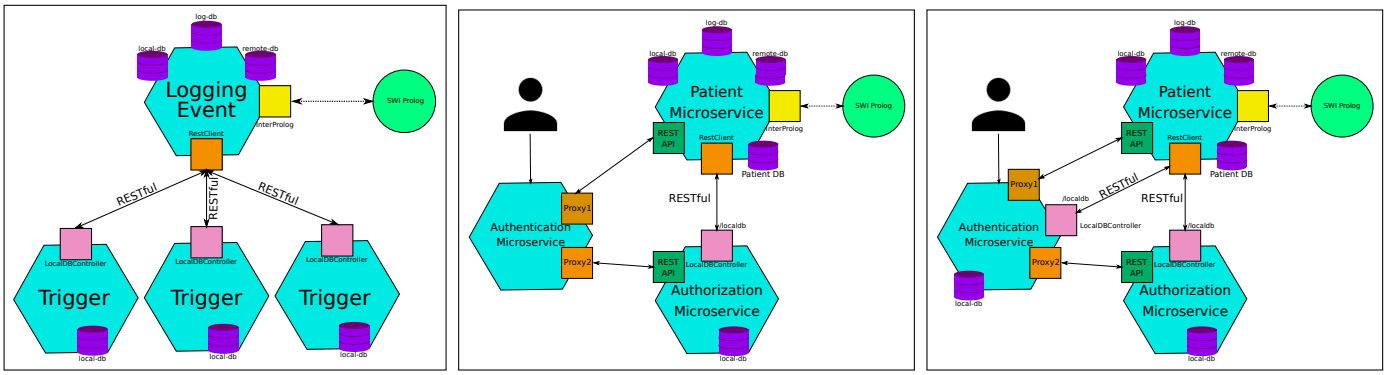
Fig. 6: Different versions of break-the-glass policy specified as a Horn clause.

defining *before* aspects for each extra trigger. Figures 7b and 7c visually describe some of the aforementioned changes to $\texttt{MRS}_{\texttt{Demo}}$ by `LogInst`, considering each version of the policy.These instrumented versions are accessible in [**?**], along with other examples of logging specifications, and their associated instrumented counterparts.

IV. Related Work

Audit logging in microservices. In recent years, constructing software in terms of decoupled microservices [13]–[16] has been a trending approach in web application design and deployment, and thus different studies have been conducted on microservices security [17]–[19]. In practice, enforcing in-depth security has pushed platform-specific monitoring and logging techniques for microservices, e.g., in Azure Kubernetes Service [20] and Spring Security Framework [21], [22]. One common approach has been to establish a central logging service with data visualization capabilities [23]. Examples include a provenance logger for microservices-based applications [24], and an architecture for IoT services that includes logger microservices in Web of Objects platform [25]. Our approach in audit logging is concurrent rather than central, i.e., any microservice is able to log events based on preconditions that may occur in other microservices as well as that microservice. This boosts the expressivity of the enforcible logging policies. There have been other approaches to define semantics of microservices, including Petri nets [26].

Formal study of audit logging. One line of work wrt formal study of audit logging focuses on the security of logs, in particular through cryptographic techniques, e.g., to establish forward secrecy [27], to ensure trustworthiness of logs [28], [29], and to preserve privacy in auditing [30]. These techniques assume that logs are given in the first place to be secured. However, in this paper we aim at developing a tool to generate audit logs according to a provably correct model, and thus security of the logged data is orthogonal to it.



(a) Structure of the logging event and trigger microservices, instrumented by `LogInst`.

(b) $\texttt{MRS}_{\texttt{Demo}}$ instrumented by `LogInst` using versions 1 and 3 in Figure 6.

(c) $\texttt{MRS}_{\texttt{Demo}}$ instrumented by `LogInst` using version 2 in Figure 6.

Fig. 7: Architecture of microservices after instrumentation.

Another line of work uses logical frameworks to establish accountability in access to system resources. Examples include a framework to enforce accountability goals in discretionary access control [31], accountability wrt access to personal information based on owner-defined usage policies [32], distributed accountability based on turn-based games [33], and logging the proof of having access to system resources [34], [35]. Another related area of work is the language-level analysis of generated audit logs [36], [37].

Correct audit logging. Information algebra [4] has been used to describe the semantics of audit logging [5] for linear process execution that defines notion of correctness for audit logs, along with an instrumentation model that guarantees to generate correct audit logs. Lately, an instrumentation model has been proposed for concurrent systems based on the information-algebraic semantic framework [6]. This model enjoys correct audit logging, which has been the basis for our proposed instrumentation tool.

Provenance. Audit logging is closely associated with the notion of provenance tracking [38]–[40]. Recent works in this area include ClearScope [41] a provenance tracker for Android devices, CamFlow [42] an auditing and provenance capture utility in Linux, and AccessProv [43] an instrumentation tool to discover vulnerabilities in Java applications.

V. Conclusion

In this paper, we have proposed a tool, `LogInst`, to instrument microservices-based applications that are deployed in Java Spring Framework for audit logging purposes. Our tool is based on an implementation model for concurrent systems that guarantees correctness of audit logging, using an information-algebraic semantic framework. `LogInst` receives the application source code, consisting of two or more microservices, along with a specification of audit logging requirements in JSON format. `LogInst` parses the JSON specification and extracts Horn clauses that are fed to a logic programming engine. `LogInst` instruments the microservices according to this specification. The instrumentation includes adding new repositories to the corresponding microservices, extending RESTful APIs on those microservices for logging-related communications, and weaving audit logging into the control flow of microservices using AspectJ. Our case study is a medical records system in which certain actions in authorization microservice may trigger logging events in access to patient medical data.

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