A Real-Time, Flexible Logging and Monitoring Infrastructure for MonPoly

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Chapter 1

Introduction

1.1 Motivation

Our digital world consists of many hardware and software systems. These systems are continuously performing a lot of actions. For a variety of reasons one might want to monitor those actions and make sure that they do not violate some predefined specification. One way to achieve this is to log relevant actions and analyze these logs. Such monitoring is part of the field of Runtime Verification (RV) [1]. The analysis of the logs can either be done *online* while the system is running or it can be done *offline* after the system has terminated.

Consider a social media site. It is bound by an increasing number of privacy laws and regulations. Let a hypothetical piece of regulation be that a user's location information may not be used to tailor advertisements to that user unless the user gave specific permission. Then the site could log every time instance when a user's location data is accessed and the purpose of the access. In words the predefined specification the site wants to check then could be: "If a user's location data is accessed and the purpose of the access is for tailoring advertisements, the user must have previously given permission for there location data to be used for advertising purposes".

MonPoly [7] is a tool for such runtime monitoring. It can perform both online and offline monitoring. For online monitoring it accepts new events via standard input. For offline monitoring it can read a timestamped log file that was generated during the runtime of a system. It uses Metric First-Order Temporal Logic (MFOTL) [5, 3, 9] as a formal specification language, which we will introduce in the background chapter.

MonPoly in its current state has some limitations that we want to improve. For one, online monitoring can not easily be done on a different machine from which the system is running on. This does not fit well with the way many modern systems operate. Modern systems are often very distributed. It is common that different functions of a system run on different machines. These can be physical or virtual machines and more and more applications are also containerized with technologies like Docker. Oftentimes multiple machines also perform the same kind of operation, e.g. caching servers. MonPoly in its current state does not fit well into this world of interconnected microservices.

Another issue that MonPoly faces currently is data portability. MonPoly can store its execution state to disk before stopping. It can also restore that state, but only on the same system as the way it stores the state is tied to the physical memory configuration of the system. We would like the ability to have MonPoly run on one system, then shut it down and restart it on a different system where it resumes with the same state that the monitor had before shutting down on the first system.

Further there is no built-in way to update the monitored policy. We aim to offer a first method for policy changes with minimal overhead in time and compute power.

We improve MonPoly in these aspects by building a wrapper that connects it with a database and also provides a new, more web friendly, interface to MonPoly. It has always been possible to use a database for logging purposes in addition to MonPoly. We integrate the logging and monitoring functionality into a single tool. This reduces potential redundancies and gives us more flexibility on the monitoring side.

MonPoly works with timestamped and tabular data. We make use of this fact for the choice of database. The temporal nature of the data leads us to time series databases [**empty citation**], which, as the name implies, are optimized for temporal data. By far the most common type of databases are relational databases. This is a great coincidence, because relational databases make extensive use of tables for storing data. We looked at a few different relational time series databases. In the end we opted for QuestDB [15].

1.2 Our Approach

We extend MonPoly with a web based wrapper written in Python using Flask [11]. This wrapper provides a REST API [10] to MonPoly. The wrapper accepts incoming events and manages both the monitoring and logging to the database. We aim for a consistent state between the database and the monitor. Consistent here means that an event is stored in the database if and only if it has been properly processed by the monitor.

The database connection allows us to stop MonPoly on one system and resume the monitoring on a different system, by querying the database.

To facilitate some functions of the wrapper we have added some extensions to MonPoly itself. We added flags to MonPoly to print the schema of a given signature in SQL as well as JSON format. One of our aims was fault tolerance and for this we added some options to keep that would keep the monitor running instead of exiting when encountering certain issues. For the policy change we need to potentially reload a lot of events into the monitor. We added an option to first read events from a file and then switch to standard input. Previously the monitor would either read a file and then stop or continuously read from standard input. Another addition are capabilities to get the relative interval of a MFOTL formula and also to get the relative intervals of predicates in a formula. We have begun work on a different method of doing a policy change by changing only parts of a formula while MonPoly keeps running and can keep the state of the formula parts that are unchanged.

1.3 Contributions

We package MonPoly as a web app and add a new API that offers greater flexibility in how MonPoly can be used. Through this wrapper we connect MonPoly to a database. The addition of a database gives us more options in terms of data portability.

We make use of relative intervals [6] to get a good over approximation of the data needed to continue monitoring a specific formula.

With the database we can offer a first version of a policy change by stopping the monitor and starting a new instance with the events within the relative interval of the new policy already loaded.

The code base of the wrapper is in a GitLab repository [12]. The repository contains over 1300 lines of Python code. Our extended MonPoly is a branch of the development version of MonPoly on BitBucket [8]. We have added over 500 lines of code to MonPoly.

Chapter 2

Background

2.1 Metric First-Order Temporal and Dynamic Logic

As mentioned in the introduction, Metric First-Order Temporal Logic (MFOTL) [5, 3, 9] is used as a policy specification language by MonPoly. Here we give a quick overview of MFOTL. MFOTL is well suited to express a variety of policies one might want to monitor. It combines First Order Logic (FOL) with metric temporal operators. The metric aspect of these operators is the interval I they are bound by. This interval denotes a time frame in which the formula needs to be satisfied.

Metric First-Order *Dynamic* Logic (MFODL) [2] is an even more expressive specification language than MFOTL. MFODL introduces the notion of regular expressions. It is more general than MFOTL and in theory the temporal operators from MFOTL could be replaced by the two more powerful operators introduced by MFODL. In practice, it is often useful to keep the basic temporal operators as we can apply specialized optimizations to them that cannot be done with regular expressions.

Basin et al. [4] extends MFOTL with aggregations. Aggregation operations like SUM are commonly seen in database contexts. When considering an example like a monthly spending limit for a credit card it becomes clear how aggregations can be useful in policy monitoring.

2.1.1 Syntax and Semantics

Let's recall the syntax and semantics of MFOTL [5, 3, 20] as well as MFODL [2]. Like Basin et al. [3] we let $\mathbb{I}$ be the set of nonempty intervals over $\mathbb{N}$. We use the common interval definition with round brackets for open intervals and square brackets for closed ones, e.g. $[a, b) := \{x \in \mathbb{N} \mid a \leq x < b\}$. A signature S, as defined by Basin et al. [3], is a tuple (C, R, ι). C is a finite set of constant symbols, R is a finite set of predicates, and $\iota : R \to C$ is a function that assigns each predicate $r \in R$ an arity $\iota(r)$. C and R are disjoint, i.e. $C \cap R = \emptyset$. Let $S = (C, R, \iota)$ be a signature and V a finite set of variables with $V \cap (C \cup R) = \emptyset$. Now we have enough information to restate the definition of an MFOTL formula (Definition 2.1 in Basin et al. [3]). Let $\circ$ be any ordering relation over $V \cup C$, i.e. $\approx$, $\prec$, $\preceq$. Basin et al. [3] only included the equality relation, the other comparisons were added in [2].

Definition 1 *The MFOTL formulas over S are inductively defined in the following way.*

(i) For $t, t' \in V \cup C$, $t \circ t'$ is a formula.

(ii) For $r \in R$ and $t_1, t_2, \ldots, t_{\iota(r)} \in V \cup C$, $r(t_1, t_2, \ldots, t_{\iota(r)})$ is a formula.

(iii) For $x \in V$, if ϕ and ψ are formulas then $(\neg\phi), (\phi \vee \psi)$, and $(\exists x.\phi)$ are formulas.

(iv) For $I \in \mathbb{I}$, if ϕ and ψ are formulas then $(\bullet_I \phi), (\bigcirc_I \phi), (\phi \, \mathcal{S}_I \, \psi)$, and $(\phi \mathcal{U}_I \, \psi)$ are formulas.

Definition 1 omits common first order logical operators $\wedge$ ("and") and $\forall$ ("for all"). These can be constructed as syntactic sugar from the three FOL operators negation, or, and the exists quantifier. The metric temporal operators in MFOTL are $\mathcal{U}_I$ ("until"), $\mathcal{S}_I$ ("since"), $\bullet_I$

("previous"), and $\bigcirc_I$ ("next"). Similarly to FOL the four MFOTL operators can also be used to construct other convenient operators such as $\blacklozenge_I$ ("once"), $\Diamond_I$ ("eventually"), $\Box_I$ ("always"), and $\blacksquare_I$ ("historically"). See Basin et al. [3] for the concrete derivations of these additional operators.

The subscript I of the temporal operators specifies the time interval in the past or the future in which a formula must be satisfied. For the evaluation of a formula Basin et al. [3] introduces the notion of a structure $\mathcal{D}$ over a signature $S = (C, R, \iota)$. It consists of the domain $|\mathcal{D}| \neq \emptyset$ and interpretations $c^{\mathcal{D}} \in |\mathcal{D}|$ and $r^{\mathcal{D}} \in |\mathcal{D}|$, for each $c \in C$ and $r \in R$. Basin et al. [3] further defines a temporal structure as a pair $(\bar{\mathcal{D}}, \bar{\tau})$ whith $\bar{\mathcal{D}} = (\mathcal{D}_0, \mathcal{D}_1, \dots)$ is a sequence of structures over S and $\bar{\tau} = (\tau_0, \tau_1, \dots)$ is a sequence of non-negative integers (*time stamps*) with the following 3 properties.

1. The sequence is monotonically increasing, i.e. $\forall i.\tau_i \leq \tau_{i+1}$. Moreover $\bar{\tau}$ makes progress for every $\tau \in \mathbb{N}$ there is some i such that $\tau < \tau_i$.
2. $\bar{\mathcal{D}}$ has constant domains, that is, for all $i \geq 0$, $|\mathcal{D}_i| = |\mathcal{D}_{i+1}|$.
3. Each constant symbol $c \in C$ has a rigid interpretation, that is, for all $i \geq 0$, $c^{\mathcal{D}_i} = c^{\mathcal{D}_{i+1}}$.

A temporal structure is sometimes called a trace and denoted σ. It is important to note the difference between *time stamps* and *time points*. Time points are the combination of a time stamp τ_i and a structur $\mathcal{D}_i$, where i is the index by which a time point is described. Since the domain of the structures $\mathcal{D}_i$ and the valuation of constants $c \in C$ do not change they are denoted as $|\bar{\mathcal{D}}|$ and $c^{\bar{\mathcal{D}}}$ respectively. Basin et al. defines a *valuation* as a mapping $v : V \to |\bar{\mathcal{D}}|$. And for a variable vector $\bar{x} = (x_1, \dots, x_n)$, and $\bar{d} = (d_1, \dots, d_n) \in |\bar{\mathcal{D}}$ it defines the notation $v[\bar{x} \mapsto \bar{d}]$ for the valuation that maps x_i to d_i for $1 \leq i \leq n$. Further it uses a notational hack to also apply a valuation v to constant symbols $c \in C$ where $v(c) = c^{\bar{\mathcal{D}}}$. For convenience we restate Definition 2.2 from Basin et al. [3]. Since we changed the definition of a formula to include ordering relations $(\prec, \preceq)$ instead of only equality $(\approx)$, we append this definition to allow for that. These additions are also in Figure 1 of Basin et. al [2].

Definition 2 *Let $(\bar{\mathcal{D}}, \bar{\tau})$ be a temporal structure over the signature $S = (C, R, \iota)$, with $\bar{\mathcal{D}} = (\mathcal{D}_0, \mathcal{D}_1, \dots)$ and $\bar{\tau} = (\tau_0, \tau_1, \dots)$, ϕ a formula over S, v a valuation, and $i \in \mathbb{N}$. We define the relation $(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \phi$ inductively as follows.*

$$
\begin{aligned}
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models t \approx t' && \text{iff } v(t) = v(t') \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models t \prec t' && \text{iff } v(t) < v(t') \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models t \preceq t' && \text{iff } v(t) \leq v(t') \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models r(t_1, \dots, t_{\iota(r)}) && \text{iff } (v(t_1), \dots, v(t_{\iota(r)})) \in r^{\mathcal{D}_i} \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\neg\psi) && \text{iff } (\bar{\mathcal{D}}, \bar{\tau}, v, i) \not\models \psi \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\psi \vee \psi') && \text{if } (\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \psi \text{ or } (\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \psi' \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\exists x.\psi) && \text{iff } (\bar{\mathcal{D}}, \bar{\tau}, v[x \mapsto d], i) \models \psi \text{ for some } d \in |\bar{\mathcal{D}}| \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\bullet_I \psi) && \text{iff } i > 0, \tau_i - \tau_{i-1} \in I, \text{ and } (\bar{\mathcal{D}}, \bar{\tau}, v, i-1) \models \psi \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\bigcirc_I \psi) && \text{iff } \tau_{i+1} - \tau_i \in I \text{ and } (\bar{\mathcal{D}}, \bar{\tau}, v, i+1) \models \psi \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\psi \, \mathcal{S}_I \, \psi') && \text{iff for some } j \leq i, \tau_i - \tau_j \in I, (\bar{\mathcal{D}}, \bar{\tau}, v, j) \models \psi' \text{ and} \\
& && \quad (\bar{\mathcal{D}}, \bar{\tau}, v, k) \models \psi \text{ for all } k \in \mathbb{N} \text{ with } j < k \leq i \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models (\psi \, \mathcal{U}_I \, \psi') && \text{iff for some } j \geq i, \tau_j - \tau_i \in I, (\bar{\mathcal{D}}, \bar{\tau}, v, j) \models \psi' \text{ and} \\
& && \quad (\bar{\mathcal{D}}, \bar{\tau}, v, k) \models \psi \text{ for all } k \in \mathbb{N} \text{ with } i \leq k < j
\end{aligned}
$$

Anologous to Definition 2 we now give the definition of an MFODL formula. The definition is based on Figure 4 of Basin et al. [2], but in a notation closer to the one we already used for MFOTL formulas. For MFODL formulas we first have to define regular expressions, as MFODL formulas depend on them.

Definition 3 *The MFODL regular expressions are defined in the following way:*

(i) *If $k \in \mathbb{N}$ then $\star^k$ is a regular expression.*

(ii) *If ϕ is a formula then $(\phi?)$ is a regular expression.*

(iii) *If ρ is a regular expression then (ρ^*) is a regular expression.*

(iv) *If ρ and σ are regular expressions then $(\rho + \sigma)$ and $(\rho \cdot \sigma)$ are regular expressions.*

With this we extend Definition 1 to include MFODL formulas.

Definition 4 *The MFODL formulas over S are inductively defined in the following way.*

(i) *MFOTL formulas are also MFOTL formulas*

(ii) *For $I \in \mathbb{I}$, if ρ is a regular expression then $(\blacktriangleleft_I \rho)$ and $(\triangleright_I \rho)$ are formulas.*

For the evaluation of an MFODL formula we first need to define how regular expressions get evaluated. The definition is originally given through the `match` function in Figure 4 of Basin et al. [2]. We formulate the definition that is more in line with the mathematical notation we used this far.

Definition 5 *Let $(\bar{\mathcal{D}}, \bar{\tau})$ be a temporal structure over the signature $S = (C, R, \iota)$, with $\bar{\mathcal{D}} = (\mathcal{D}_0, \mathcal{D}_1, \dots)$ and $\bar{\tau} = (\tau_0, \tau_1, \dots)$, ϕ a formula over S, v a valuation, and $i, j \in \mathbb{N}$.*

$$
\begin{aligned}
&(\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \star^k && \text{iff } i = j + k \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \phi? && \text{iff } (\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \phi \text{ and } i = j \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \rho + \sigma && \text{iff } (\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \rho \text{ or } (\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \sigma \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \rho \cdot \sigma && \text{iff for some } k \in \mathbb{N}, (\bar{\mathcal{D}}, \bar{\tau}, v, i, k) \models_r \rho \text{ and } (\bar{\mathcal{D}}, \bar{\tau}, v, k, j) \models_r \sigma \\
&(\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \rho^* && \text{iff for some } l \in \mathbb{N}, o_1, \dots, o_l \in \mathbb{N}, (\bar{\mathcal{D}}, \bar{\tau}, v, i, o_1) \models_r \rho \text{ and } \dots \\
& && \quad \text{and } (\bar{\mathcal{D}}, \bar{\tau}, v, o_l, j) \models_r \rho
\end{aligned}
$$

With the help of Definition 5 we can now define the evaluation of MFODL formulas which is also given in Figure 4 of Basin et al. [2] through the `sat` function. The trace σ in the `sat` function is simply our temporal structure $(\bar{\mathcal{D}}, \bar{\tau})$. The data list v is the valuation mapping. And i specifies the current time point in both notations.

Definition 6 *Let $(\bar{\mathcal{D}}, \bar{\tau})$ be a temporal structure over the signature $S = (C, R, \iota)$, with $\bar{\mathcal{D}} = (\mathcal{D}_0, \mathcal{D}_1, \dots)$ and $\bar{\tau} = (\tau_0, \tau_1, \dots)$, ϕ a formula over S, v a valuation, and $i \in \mathbb{N}$. We define the relation $(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \phi$ inductively as follows.*

$$
\begin{aligned}
(\bar{\mathcal{D}}, \bar{\tau}, v, i) &\models \blacktriangleleft_I \rho \text{ iff for some } j \leq i, \tau_i - \tau_j \in I \text{ and } (\bar{\mathcal{D}}, \bar{\tau}, v, j, i) \models_r \rho \\
(\bar{\mathcal{D}}, \bar{\tau}, v, i) &\models \triangleright_I \rho \text{ iff for some } j \geq i, \tau_j - \tau_i \in I \text{ and } (\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \rho
\end{aligned}
$$

2.2 MonPoly

MonPoly [7] is a policy monitoring tool written in OCaml that supports MFOTL with aggregations and in its newest iterations it also has support for MFODL. MonPoly can monitor a fragment of MFOTL/MFODL where all future operators must be bounded. One major exception to that rule is an (implicit) always operator around the desired policy.

Let's return to the social media example from the introduction and look at how we would go about monitoring that policy with MonPoly. We recall our description in words: "If a user's location data is accessed and the purpose of the access is for tailoring advertisements, the user must have previously given permission for their location data to be used for advertising purposes." In MonPoly a policy is tied to a signature. A signature can be compared with a database schema and describes the arity and types of possible events. So let's consider a possible signature for our example:

```
loc_accessed(user_id: int, purpose: string)
perm_granted(user_id: int)
perm_revoked(user_id: int)
```

Figure 2.1: Example MonPoly Signature

This is a basic signature with 3 predicates. The first one means that a users location data has been used for a specified purpose. The last two events get triggered when a user either grants or revokes permission for their location data to be used for advertising purposes. Let's now define the policy in a formal manner.

$$\square(\texttt{loc\_accessed(i, "advertising")} \implies (\blacklozenge_{[0,\infty)}\texttt{perm\_granted(i)} \\ \wedge\neg(\texttt{perm\_revoked(i)}\ \mathcal{S}_{[0,\infty)}\ \texttt{perm\_granted(i)})))$$

For MonPoly we first get rid of the surrounding $\square$, because MonPoly implicitly adds an always-operator around any policy. The remaining formula in MonPoly syntax is the following:

```
loc_accessed(i, "advertising")
IMPLIES
(
    (ONCE[0,*) perm_granted(i))
    AND
    (NOT (perm_revoked(i) SINCE[0,*) perm_granted(i)))
)
```

Figure 2.2: Example MonPoly Policy

While MonPoly cannot actually monitor this formula directly, it can monitor the negation of this formula. For this on can use the `-negate` flag when running MonPoly.

2.3 Time Series Databases

Time series databases are a class of databases optimized for timestamped data. For example, they optimize for data retrieval within a certain time range. With the advance of internet of things devices with built-in sensors time series databases are experiencing explosive growth. And as we have established they happen to fit well with our monitoring goals. There are many different options of time series databases available. We were looking for something with good performance, good support for tables of data, and good usability. We have opted for QuestDB [15].

2.3.1 QuestDB

QuestDB uses a column-based storage model [19]. It supports the PostgreSQL wire protocol [17] for querying and inserting data. This is the same protocol used by the popular relational database PostgreSQL [14]. The support for SQL as a query language is of great use, because SQL is the most widely used and taught database query language. PostgreSQL is in itself a very popular dialect of SQL and thus has a lot of tooling available which can also be used with QuestDB. It further provides a REST API [18] and has a web console for both inserting and querying data. For best performance it supports the InfluxDB Line Protocol [16, 13] with client libraries for most popular modern programming languages. InfluxDB is itself a time series database and the line protocol is a write protocol developed by and for InfluxDB optimized for time series data. The QuestDB client liabries for different programming languages are implementations of the InfluxDB line protocol by QuestDB. QuestDB recommends using the Line Protocol for the best write performance, compared to the other methods of writing data. The Line Protocol cannot be used to query data. For that the PostgrSQL Wire Protocol is the recommended method. QuestDB is written in Java, open source, and licensed under the Apache 2.0 license.

2.3.2 Time Series Databases for Runtime Monitoring

In this section we explore how a timeseries database can be utilized in the context of runtime monitoring. We will contrast policies and database queries, as well as signatures and database schemas. An important and possibly counter intuitive thing is that MFOTL is not any more expressive than FOL. In fact they have the same expression strength, i.e. any MFOTL formula can be expressed as a FOL formula and vice versa. Any FOL formula is by definition also a MFOTL formula. The other way around any trace in MFOTL can be simulated in FOL by extending predicates with two attributes for the time point and time stamp. Take for example the formula $\phi = \bullet_{[a,b)} P()$ where P is a predicate with arity 0. ϕ is equivalent to the FOL formula $\phi' = P(t_s, t_p) \wedge \exists t'_s . P(t'_s, t_p - 1) \wedge a \leq t_s - t'_s < b$.

It is relatively straight forward to create a database schema from a signature like the one in Figure 2.2. We create one table per predicate. The predicate name is used as the table name. The columns and their types are given by the attributes. MonPoly allows for optional attribute names, we disregard those, if they are present and rely on the ordering of attributes. We need two additional columns, one for the time point, i.e. an integer index, and one for the time stamp when the event occurred. One additional table keeping track of all time points and their time stamps is necessary, because a time point could occur without any event attached to it, if we only had the events stored, we would lose any record of such time points. And any time point can influence the evaluation of a formula. This time stamp and time point table technically makes it redundant to store the time stamps with every predicate, since the mapping from time point indices to time stamps is injective. But QuestDB requires a time stamp column and it is also beneficial for performance as QuestDB is optimized for queries on time ranges.

The database schema as SQL create statements for our example policy from Figure 2.2 can be seen in Figure 2.3.2. The `timestamp()` function is a special extension to SQL for QuestDB. It specifies the column that is used as the dedicated time stamp in a table. If it is not specified an additional time stamp column would get added. By default no partitioning would be used.

```
CREATE TABLE perm_revoked(x1 INT,
                          time_stamp TIMESTAMP,
                          time_point INT)
                          timestamp(time_stamp);
CREATE TABLE perm_granted(x1 INT,
                          time_stamp TIMESTAMP,
                          time_point INT)
                          timestamp(time_stamp);
CREATE TABLE loc_accessed(x1 INT, x2 STRING,
                          time_stamp TIMESTAMP,
                          time_point INT)
                          timestamp(time_stamp);
CREATE TABLE ts( time_stamp TIMESTAMP,
                 time_point INT)
                 timestamp(time_stamp);
```

Figure 2.3: SQL Schema for Example Policy

Chapter 3

Architecture

In this section we introduce the general architecture of our wrapper for MonPoly. A more in depth look at the specific technical implementation will be provided in the implementation section. In general, we have three components for this project. On one hand we have the MonPoly with a few extensions. On the other hand is QuestDB. Our wrapper acts as the glue between the two. In addition the wrapper also provides a new interface to MonPoly in the form of a REST API. Figure 3.1 shows the structure of the MonPoly wrapper.

3.1 Wrapper

The wrapper can be run directly on a system with MonPoly installed. The alternative and more portable way to run it is with a docker container. To interact with the wrapper a user can use the provided REST API by sending web requests.

The wrapper runs MonPoly as a subprocess and handles all interactions with MonPoly itself. Incoming events are first parsed and checked on some major formatting errors. When the formatting is deemed acceptable the events get forwarded to MonPoly on a per time stamp basis. If MonPoly reports an issue with a certain time stamp, either it is out of order or one event at that timestamp does not comply with the given signature, this time stamp gets ignored by MonPoly, and in turn the wrapper discards it as well. If no issue is detected with a timestamp all events in at that timestamp get forwarded to the database.

3.2 The REST API

The interface to the wrapper is a REST API. We will now introduce the main endpoints and give brief usage examples.

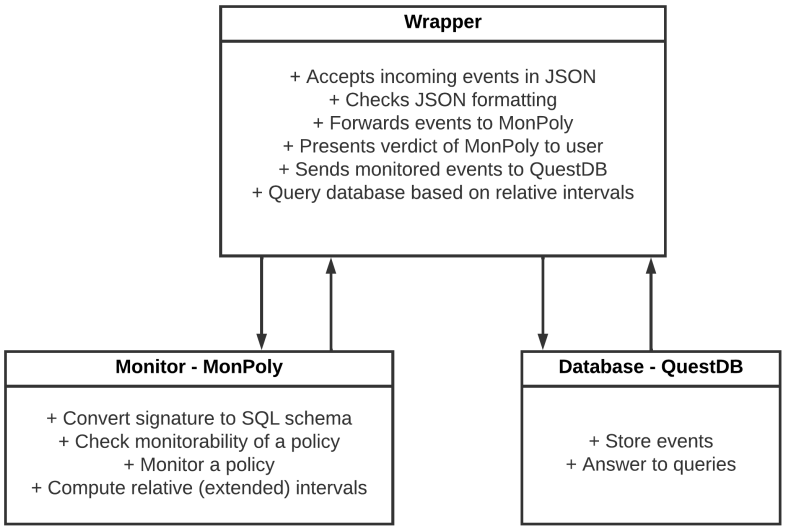

Figure 3.1: Illustration of the project structure

Chapter 4

Algorithms

4.1 Policy Change

This section gives a high level view of our policy change method. The individual parts of the policy change will be explained in the following sections of this chapter. We have a running instance of MonPoly monitoring some policy. The user asks the wrapper to monitor a new policy. The wrapper checks the monitorability of the new policy against the existing policy. If it is not monitorable the wrapper keeps the current instance of MonPoly running and reports the issue with the new policy to the user. Otherwise the wrapper uses MonPoly to get the extended relative intervals of the new policy. Then these extended relative intervals get converted to SQL queries and the wrapper runs these queries on QuestDB. The response from QuestDB gets converted into a MonPoly log file. Next the wrapper stops the current iteration of MonPoly and starts a new one that first reads the created log file. At this point the policy change is done, and the wrapper can continue with its normal operation.

4.2 Relative Intervals

First we append the definition of relative intervals from Basin et al. [6] to include all operators currently supported by MonPoly. Namely we add definitions for the MFODL operators. Intervals are defined over $\mathbb{Z}$ and can either be open or closed. The operators $\oplus$ and $\Cup$ are defined the same way as in Basin et al. [6]. Let I and J be some arbitrary intervals then $I \oplus J := \{i+j \mid i \in I \text{ and } j \in J\}$ and $I \Cup J$ is the smallest interval containing all values in both I and J.

Definition 7 *The relative interval of the formula ϕ, $\mathrm{RI}(\phi) \subseteq \mathbb{Z}$ is defined recuresively over the formula structure:*

$$\mathrm{RI}(\phi) = \begin{cases} \{0\} & \text{if } \phi \text{ is an an atomic formula,} \\ \mathrm{RI}(\psi) & \text{if } \phi \text{ is of the form } \neg\psi,\ \exists x.\psi, \\ & \text{or } \forall x.\psi, \\ \mathrm{RI}(\psi) \Cup \mathrm{RI}(\chi) & \text{if } \phi \text{ is of the form } \psi \vee \chi, or \psi \wedge \chi, \\ (-b, 0] \Cup ((-b, -a] \oplus \mathrm{RI}(\psi)) & \text{if } \phi \text{ is of the form } \bullet_{[a,b)}\psi, \\ [0, b) \Cup ([a, b) \oplus \mathrm{RI}(\psi)) & \text{if } \phi \text{ is of the form } \bigcirc_{[a,b)}, \\ (-b, 0] \Cup ((-b, 0] \oplus \mathrm{RI}(\psi)) \Cup ((-b, -a] \oplus \mathrm{RI}(\chi)) & \text{if } \phi \text{ is of the form } \psi\, \mathcal{S}_{[a,b)} \chi, \\ [0, b) \Cup ([0, b) \oplus \mathrm{RI}(\psi)) \Cup ([a, b) \oplus \mathrm{RI}(\chi)) & \text{if } \phi \text{ is of the form } \psi\, \mathcal{U}_{[a,b)}\, \chi, \\ [0, b) \Cup ([0, b) \oplus \mathrm{RI}_{reg}(\rho)) & \text{if } \phi \text{ is of the form } \triangleright_{[a,b)}\, \rho, \text{ and} \\ (-b, 0] \Cup ((-b, 0] \oplus \mathrm{RI}_{reg}(\rho)) & \text{if } \phi \text{ is of the form } \blacktriangleleft_{[a,b)}\, \rho. \end{cases}$$

We recursively define the relative interval of regular expressions as seen in Basin et al. [2] in the following way.

Definition 8 *The relative interval of the regular expression ρ, $\mathrm{RI}_{reg}(\rho) \subseteq \mathbb{Z}$ is defined recursively over the structure of the regular expression:*

$$\mathrm{RI}_{reg}(\rho) = \begin{cases} \{0\} & \text{if } \rho \text{ is of the form } \star^k, \\ \mathrm{RI}(\phi) & \text{if } \rho \text{ is of the form } \phi?, \\ \mathrm{RI}_{reg}(\sigma) \Cup \mathrm{RI}_{reg}(\tau) & \text{if } \rho \text{ is of the form } \sigma + \tau \text{ or } \sigma \cdot \tau, \text{ and} \\ \mathrm{RI}_{reg}(\sigma) & \text{if } \rho \text{ is of the form } \sigma^*. \end{cases}$$

4.2.1 Correctness

We want to show that it is sufficient to extract all time points with a time stamp in the relative interval $\mathrm{RI}(\phi)$ for a formula ϕ from a trace to evaluate ϕ. Lemma A.4 in Basin et al. [6] provides exactly this. The lemma says that the evaluation of a formula ϕ is the same on two different temporal structures (traces) for the time point with index i in the first structure and the time point with index $i - c$ in the second structure if they are $(RI(\phi), c, i)$-overlapping as defined by Definition A.4 in Basin et al. [6].

For convenience we restate Lemma A.4 and the definitions it requires here. First we recall Definition A.2 from Basin et al. [6].

Definition 9 *Let $T \subseteq \mathbb{Z}$ be an interval and $(\bar{\mathcal{D}}, \bar{\tau})$ a trace. The T-slice of $(\bar{\mathcal{D}}, \bar{\tau})$ is the time slice $(\bar{\mathcal{D}}', \bar{\tau}')$ of $(\bar{\mathcal{D}}, \bar{\tau})$, where $s : [0, l) \to \mathbb{N}$ is the function $s(i') = i' + c, l = |\{i \in \mathbb{N} \mid \tau_i \in T\}|$ and $c = \min\{i \in \mathbb{N} \mid \tau_i \in T\}$. We also require that $\tau'_l \notin T$ and $\mathcal{D}'_{i'} = \mathcal{D}_{s(i')}$, for all $i' \in [0, l)$.*

We also need Definition A.4 from Basin et al. [6].

Definition 10 *Let $I \subseteq \mathbb{Z}$ be an interval and $c, i \in \mathbb{N}$. The temporal structures $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are (I, c, i)-overlapping if the following conditions hold:*

1. *$j \geq c, \mathcal{D}_j = \mathcal{D}'_{j-c}$, and $\tau_j = \tau'_{j-c}$, for all $j \in \mathbb{N}$ with $\tau_j - \tau_i \in I$.*
2. *$\mathcal{D}_{j'+c} = \mathcal{D}'_j$, and $\tau_{j'+c} = \tau'_{j'}$, for all $j' \in \mathbb{N}$ with $\tau'_{j'} - \tau_i \in I$.*

Lemma A.1 in Basin et al. [6] is useful, we restate it here.

Lemma 1 *For every formula ϕ, $0 \in \mathrm{RI}(\phi)$.*

The proof that this holds is a structural induction over the formula structure for both MFOTL and MFODL, except that the MFODL part requires a similar lemma for regular expressions.

Lemma 2 *For every regular expression ρ, $0 \in \mathrm{RI}_{reg}(\rho)$.*

Proof the first case is a regular expression $\rho = \star^k$ for $k \in \mathbb{N}$. Tiviallay $0 \in \mathrm{RI}_{\mathrm{reg}}(\rho) = \mathrm{RI}_{\mathrm{reg}}(\star^k) = 0$. Next $\rho = \phi?$ for a formula ϕ. $\mathrm{RI}_{\mathrm{reg}}(\rho) = \mathrm{RI}_{\mathrm{reg}}(\phi?) = \mathrm{RI}(\phi)$. By Lemma 1 $0 \in \mathrm{RI}(\phi)$ and thus $0 \in \mathrm{RI}_{\mathrm{reg}}(\rho)$. Now we consider $\rho = \sigma \Cup \tau$ for two regular expressions σ and τ. By the induction hypothesis (IH) $0 \in \mathrm{RI}_{\mathrm{reg}}(\sigma)$ and $0 \in \mathrm{RI}_{\mathrm{reg}}(\tau)$. Thus $0 \in \mathrm{RI}_{\mathrm{reg}}(\sigma) \Cup \mathrm{RI}_{\mathrm{reg}}(\tau) = \mathrm{RI}_{\mathrm{reg}}(\rho)$. Finally $\rho = \sigma*$ for a regular expression σ. By IH $0 \in \mathrm{RI}_{\mathrm{reg}}(\sigma) = \mathrm{RI}_{\mathrm{reg}}(\rho)$. Therefore Lemma 2 holds for all regular expressions.

And finally Lemma A.4 itself.

Lemma 3 *Let ϕ be a formula and $(\bar{\mathcal{D}}, \bar{\tau}), (\bar{\mathcal{D}}', \bar{\tau}')$ temporal structures. If $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are $(\mathrm{RI}(\phi), c, i)$-overlapping, for some c and i, then for all valuations v, it holds that $(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \phi$ iff $(\bar{\mathcal{D}}', \bar{\tau}', v, i) \models \phi$.*

A proof by structural induction on the structure of MFOTL formulas for Lemma A.4 [6] / Lemma 3 is provided in Basin et al. [6]. We will extend this proof to also include the MFODL formulas as we defined them in Defintion 3.

For this we need an analogous lemma that works for regular expressions.

Lemma 4 *Let ρ be a regular expression and $(\bar{\mathcal{D}}, \bar{\tau}), (\bar{\mathcal{D}}', \bar{\tau}')$ temporal structures. If $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are $(\mathrm{RI}_{reg}(\rho), c, i)$-overlapping, for some c and i, then for all valuations v and $j \in \mathbb{N}$, it holds that $(\bar{\mathcal{D}}, \bar{\tau}, v, i, j) \models_r \rho$ iff $(\bar{\mathcal{D}}', \bar{\tau}', v, i - c, j - c) \models_r \rho$.*

Proof Note that $(\bar{\mathcal{D}}', \bar{\tau}', v, i-c, j-c) \models_{\mathrm{r}} \rho$ is defined.

We write $\sigma = (\bar{\mathcal{D}}, \bar{\tau})$ and $\sigma' = (\bar{\mathcal{D}}', \bar{\tau}')$ as short hand for the two temporal structures. With the help of Lemma 4 we now complete the proof for Lemma 3 with MFODL formulas. We continue the proof for the case $\phi = \blacklozenge_{[a,b)}\ \rho$ where ρ is a regular expression. Let σ and σ' are $(\mathrm{RI}(\phi), c, i)-$overlapping. Where $\mathrm{RI}(\phi) = \mathrm{RI}(\blacklozenge_{[a,b)}\ \rho) = (-b, 0] \Cup ((-b, 0] \oplus \mathrm{RI}_{\mathrm{reg}}(\rho))$.

$$
\begin{aligned}
(\sigma, v, i) \models \phi \quad &\iff \quad (\sigma, v, i) \models \blacklozenge_{[a,b)}\ \rho \\
&\overset{\text{def 6}}{\iff} \quad j \leq i, \tau_i - \tau_j \in [a, b) \text{ and } (\sigma, v, j, i) \models_{\mathrm{r}} \rho \\
&\overset{\text{lem 4}}{\iff} \quad j \leq i, \tau_i - \tau_j \in [a, b) \text{ and } (\sigma', v, j, i) \models_{\mathrm{r}} \rho
\end{aligned}
$$

4.3 Relative Interval Extension

This idea of relative intervals can already filter an existing trace down to a much smaller one by removing events that are unnecessary for the evaluation of a given policy. We expand on this by creating and using a data structure that allows us to select an even smaller sub trace with the same effect of not changing the truth value of the policy.

First we move from one relative interval for an entire policy to one relative interval per predicate occurring in a policy. We break this down further. Every predicate comes with a number of attributes as defined in the signature. Some attributes are potentially constant.

Looking back at our policy from Figure 2.2, `"advertising"` is one such constant attribute in the predicate `loc_accessed`. This means any occurrence of the predicate `loc_accessed` where the second attribute is not `"advertising"`, has no influence on our policy and is therefore not needed in a potential sub trace. We check every predicate in our policy for constant attributes. Then we take the set of different arrangements of constant and variable attributes per predicate. We define a structure that captures constant and variable attributes of a predicate.

Definition 11 *Let $S = (C, R, \iota)$ be a signature and $r \in R$ a predicate with arity $\iota(r)$. A mask for the predicate r is a tuple $m = (m_1, \ldots, m_{\iota(r)})$ with $m_1, \ldots, m_{\iota(r)} \in C \cup \{v\}$ and $v \notin V \cup C$.*

v is a placeholder value denoting attributes in the mask that have a non-constant value. Each mask has its own relative interval. For our example the masks with their corresponding relative intervals can be seen in Figure 4.3.

```
loc_accessed(*,"advertising") -> [0,0]
perm_granted(*) -> (*,0]
perm_revoked(*) -> (*,0]
```

Figure 4.1: Extended Relative Intervals of Example Policy

A `*` (asterisk) in the attributes denotes a variable value, v in Definition 11. In larger formulas there can be multiple different masks per predicate. Let $\mathcal{M}(r)$ be the set of possible masks for a predicate r.

We use a map data structure to store the predicates, masks, and their respective relative intervals.

Definition 12 *Let $S = (C, R, \iota)$ be a signature and let $\mathcal{M} : R \to \{(C \cup \{v\})^*\}$ be the function $\mathcal{M}(r) = M$ that gives the set of all possible masks M for a predicate r. An **masked predicate map** is a set $\{(k, i)\}$ where $k = (r, m)$ with $r \in R$ and $m \in \mathcal{M}(r)$ and $i \subseteq \mathbb{Z}$ is an interval over $\mathbb{Z}$.*

On this data structure we define the operators $\ddot{\Cup}$, $\dot{\Cup}$ and $\dot{\oplus}$.

Definition 13 *Let m and n be two masked predicate maps and i a positive interval, then*

$$\begin{aligned} m \,\ddot{\Cup}\, n =& \{p(l) \to (i \Cup j) \mid p(l) \to i \in m \text{ and } p(l) \to j \in n\} \\ & \cup \{p(l) \to i \mid (p(l) \to i \in m \text{ and } p(l) \in \text{keys}(m) \setminus \text{keys}(n))\} \\ & \cup \{p(l) \to i \mid (p(l) \to i \in n \text{ and } p(l) \in \text{keys}(n) \setminus \text{keys}(m))\} \\ i \,\dot{\Cup}\, m =& \{p(l) \to (i \Cup j) \mid p(l) \to j \in m\} \\ i \,\dot{\oplus}\, m =& \{p(l) \to (i \oplus j) \mid p(l) \to j \in m\} \end{aligned}$$

The notation $p(l) \to i$ denotes an element in an masked predicate map. It is equivalend to the notation $((p, l), i)$, but it better shows how we are working with a map. The keys operator gives all the first elements, the predicate name and mask tuples, in a masked predicate map. With the help of the operators $\ddot{\Cup}$, $\dot{\Cup}$ and $\dot{\oplus}$ we now give a recursive definition for our extension of relative intervals.

Definition 14 *The extended relative interval of the formula φ, $\text{ERI}(\varphi)$ is defined recursively over the formula structure:*

$$\text{ERI}(\varphi) = \begin{cases} \{\} & \text{if } \varphi \text{ is an an atomic formula and not a predicate,} \\ \{p(m) \to [0,0]\} & \text{if } \varphi \text{ is a predicate with name } p \text{ and mask } m, \\ \text{ERI}(\psi) & \text{if } \varphi \text{ is of the form } \neg\psi, \exists x.\psi, \text{ or } \forall x.\psi, \\ \text{ERI}(\psi) \,\ddot{\Cup}\, \text{ERI}(\chi) & \text{if } \varphi \text{ is of the form } \psi \vee \chi, \text{ or } \psi \wedge \chi, \\ (-b, 0] \,\dot{\Cup}\, ((-b, -a] \,\dot{\oplus}\, \text{ERI}(\psi)) & \text{if } \varphi \text{ is of the form } \CIRCLE_{[a,b)}\psi, \\ [0, b) \,\dot{\Cup}\, ([a, b) \,\dot{\oplus}\, \text{ERI}(\psi)) & \text{if } \varphi \text{ is of the form } \bigcirc_{[a,b)}, \\ (-b, 0] \,\dot{\Cup}\, ((-b, 0] \,\dot{\oplus}\, \text{ERI}(\psi)) \,\ddot{\Cup}\, ((-b, -a] \,\dot{\oplus}\, \text{ERI}(\chi)) & \text{if } \varphi \text{ is of the form } \psi \,\mathcal{S}_{[a,b)}\, \chi, \\ [0, b) \,\dot{\Cup}\, ([0, b) \,\dot{\oplus}\, \text{ERI}(\psi)) \,\ddot{\Cup}\, ([a, b) \,\dot{\oplus}\, \text{ERI}(\chi)) & \text{if } \varphi \text{ is of the form } \psi \,\mathcal{U}_{[a,b)}\, \chi, \\ [0, b) \,\dot{\Cup}\, ([0, b) \,\dot{\oplus}\, \text{ERI}_{reg}(\psi)) & \text{if } \varphi \text{ is of the form } \triangleright_{[a,b)}\, \psi, \text{ and} \\ (-b, 0] \,\dot{\Cup}\, ((-b, 0] \,\dot{\oplus}\, \text{ERI}_{reg}(\psi)) & \text{if } \varphi \text{ is of the form } \blacktriangleleft_{[a,b)}\, \psi. \end{cases}$$

And for regular expressions we define

Definition 15 *The extended relative interval of the regular expression ρ, $\text{ERI}_{reg}(\rho)$ is defined recursively over the structure of the regular expression:*

$$\text{ERI}_{reg}(\rho) = \begin{cases} \{\} & \text{if } \rho \text{ is of the form } \star^k, \\ \text{ERI}(\varphi) & \text{if } \rho \text{ is of the form } \varphi?, \\ \text{ERI}_{reg}(\sigma) \,\ddot{\Cup}\, \text{ERI}_{reg}(\tau) & \text{if } \rho \text{ is of the form } \sigma + \tau \text{ or } \sigma \cdot \tau, \text{ and} \\ \text{ERI}_{reg}(\sigma) & \text{if } \rho \text{ is of the form } \sigma^*. \end{cases}$$

4.3.1 Correctness

Analogously to regular intervals we want to use the extended relative intervals to extract (slice) a sub trace from a larger trace for a given formula that has the property that the sub trace is sufficient to evaluate the formula. We first need a few definitions and lemmata before we can proof this property.

Definition 16 *Let $\mathcal{D}$ be a structure over the signature $S = (C, R, \iota)$, $r^{\mathcal{D}} \in |\mathcal{D}|$ be an interpration for the predicate $r \in R$, and m a mask for r. The arity of r, $\iota(r)$ is the same as the length of the mask m, $|m|$. The mask $m = (m_1, \ldots, m_{\iota(r)})$ matches the interpretation $r^{\mathcal{D}} = (r_1^{\mathcal{D}}, \ldots, r_{\iota(r)}^{\mathcal{D}})$ if for all $i \in [1, \iota(r)]$ either $m_i = v$ or $m_i = r_i^{\mathcal{D}}$, where v is again the place holder value for variable values.*

Definition 17 *Let M be a masked predicate map $\tau \in \mathbb{N}$ a time stamp and $\mathcal{D}$ a structure over the signature $S = (C, R, \iota)$. Let $\mathbb{D}$ be the set of all structures over the signature S.* $\text{filter}(M, \tau, \mathcal{D}) : \mathbb{D} \to \mathbb{D}$ *is a function only keeping interprations $r^{\mathcal{D}} \in |\mathcal{D}|$ that have a matching predicate mask m and relative interval I, $(m, I) \in M$ with $\tau \in I$ as well as constant interpretations $c^{\mathcal{D}} \in |\mathcal{D}|$.*

The following lemma states that filtering a structure twice has the same effect as filtering once.

Lemma 5 *Let $\mathcal{D}$ be a structure, let M be a masked predicate map and let $\tau \in \mathbb{N}$ be a time stamp. Then* $\text{filter}(M, \tau, \text{filter}(M, \tau, \mathcal{D})) = \text{filter}(M, \tau, \mathcal{D})$.

Proof From Definition 17 we have that the constant interpretations remain untouched by the filter operation. It remains to show that the left hand side (LHS) and the right hand side (RHS) in Lemma 5 have the same interpretations for predicates. The RHS only contains interpretations for predicates from $\mathcal{D}$ that have a matching mask for which its relative interval contains τ. The LHS contains interpretations fullfilling the same constraint, but they are "sampled" from the structure $\text{filter}(M, \tau, \mathcal{D})$ instead of $\mathcal{D}$ directly. But we already established that all predicate interpretations in the filtered structure (RHS) do fullfill the condition that they have a matching mask in M whose relative interval contains τ. Therefore the LHS and RHS are equivalent and the Lemma holds.

Definition 18 *Let $T \subseteq \mathbb{Z}$ be an interval and M be a masked predicate map where for all $(m, J) \in M$, $J \subseteq T$. And let $(\bar{\mathcal{D}}, \bar{\tau})$ a trace. The MT-slice of $(\bar{\mathcal{D}}, \bar{\tau})$ is the time slice $(\bar{\mathcal{D}}', \bar{\tau}')$ of $(\bar{\mathcal{D}}, \bar{\tau})$, where $s : [0, l) \to \mathbb{N}$ is the function $s(i') = i' + c, l = |\{i \in \mathbb{N} \mid \tau_i \in T\}|$, and $c = \min\{i \in \mathbb{N} \mid \tau_i \in T\}$. We also require that $\tau'_l \notin T$ and $\mathcal{D}'_{i'} = \text{filter}(M, \tau_{s(i')}, \mathcal{D}_{s(i')})$, for all $i' \in [0, l)$.*

Definition 19 *Let $I \subseteq \mathbb{Z}$ be an interval and M be a masked predicate map where for all $(m, J) \in M$, $J \subseteq I$. Let $c, i \in \mathbb{N}$. The temporal structures $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are (M, I, c, i)-overlapping if the following conditions hold:*

1. *$j \geq c$,* $\text{filter}(M, \tau_j, \mathcal{D}_j) = \text{filter}(M, \tau'_{j-c}, \mathcal{D}'_{j-c})$ *and $\tau_j = \tau'_{j-c}$, for all $j \in \mathbb{N}$ with $\tau_j - \tau_i \in I$,*
2. $\text{filter}(M, \tau_{j'+c}, \mathcal{D}_{j'+c}) = \text{filter}(M, \tau'_{j'}, \mathcal{D}'_{j'})$ *and $\tau_{j'+c} = \tau'_{j'}$, for all $j' \in \mathbb{N}$ with $\tau'_{j'} - \tau_i \in I$,*

Like with Definition 10, two traces are (M, I, c, i)-overlapping if their *filtered* time points are the same on an interval of time stamps. The next lemma establishes that a trace and an MT-slice of that trace are (M, I, c, i)-overlapping. It is analogous to Lemma A.2 in Basin et al. [6].

Lemma 6 *Let $T \subseteq \mathbb{N}$ and $I \subseteq \mathbb{Z}$ be intervals and M be a masked predicate map where for all $(m, J) \in M$, $J \subseteq I$. Let $(\bar{\mathcal{D}}, \bar{\tau})$ a trace, and $(\bar{\mathcal{D}}', \bar{\tau}')$ a $(I \dot{\oplus} M, I \oplus T)$-slice of $(\bar{\mathcal{D}}, \bar{\tau})$. The traces $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are (M, I, c, i)-overlapping, for all $i \in \mathbb{N}$ with $\tau_i \in T$, where $c \in \mathbb{N}$ is the value in Definition 18 used by the function s.*

Proof the precondition in Definition 19, that for all intervals in M are a subset of the larger interval I is satisfied, as it is also a precondition for Lemma 6. First we show condition 1 in Definition 19. For all $i \in \mathbb{N}$ with $\tau_i \in T$ and all $j \in \mathbb{N}$ with $\tau_j - \tau_i \in I$, it holds that $\tau_j \in T \oplus I$. From $c = \min\{k \in \mathbb{N} \mid \tau_k \in T \oplus I\}$ in Definition 18, it follows that $j \geq c$. Let $j' := j - c$. It also follows from $\tau_j \in T \oplus I$ that $j' \in [0, l)$. Thus $\tau_j = \tau_{s(j')} = \tau'_{j'} = \tau'_{j-c}$. Per Definition 18 we have $\mathcal{D}'_{j'} = \text{filter}(M, \tau_j, \mathcal{D}_j)$. By Lemma 5 we have that $\mathcal{D}'_{j'} = \text{filter}(M, \tau_j, \text{filter}(M, \tau_j, \mathcal{D}_j)) = \text{filter}(M, \tau_j, \mathcal{D}'_{j'})$. Therefore it follows that $\mathcal{D}'_{j'} = \text{filter}(M, \tau'_{j'}, \mathcal{D}'_{j'})$. Thus Condition 1. of Lemma 6 is satisfied.

Next we show that Condition 2. is also satisfied. For all $i \in \mathbb{N}$ with $\tau_i \in T$ and all $j' \in \mathbb{N}$ with $\tau'_{j'} - \tau_i \in I$, it holds that $\tau'_{j'} \in T \oplus I$. Since $\tau'_l \notin T \oplus I$, it follows that $j' \in [0, l)$. Therefore $\tau_{j'+c} = \tau_{s(j')} = \tau'_{j'}$. From Definition 19 it follows that $\mathcal{D}$ ...

...

Analogous to Lemma A.3 in Basin et al. [6] the following Lemma states that any overlapping traces still overlap, also overlap on parts of of the overlapping section.

...

Lemma 7 *Let $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ be two traces that are (M, I, c, i)-overlapping, for some masked predicate map M, $I \in \mathbb{Z}$, $c \in \mathbb{N}$, and $i \in \mathbb{Z}$. Then $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are (M, K, c, k)-overlapping, for each $k \in \mathbb{N}$ with $\tau_k - \tau_i \in I$ and $K \subseteq \{\tau_i - \tau_k\} \oplus I$.*

...

Proof ...

With this we get to the key Lemma that we rely on to make our optimization when selecting and querying a subtrace from the database. It is analogous to Lemma A.4 in Basin et al. [6].

Lemma 8 *Let ϕ be a formula and $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ temporal structures. If $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are $(\mathrm{ERI}(\phi), \mathrm{RI}(\phi), c, i)$-overlapping, for some c and i, then for all valuations v, it holds that $(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models \phi$ iff $(\bar{\mathcal{D}}', \bar{\tau}', v, i - c) \models \phi$.*

This Lemma applies to MFOTL formulas. It can be extended to MFODL as well, but it needs a mutually recursive extensions to include regular expressions. We focus on the core MFOTL formulas.

Proof First we note that for the same reason as in Lemma A.4 in Basin et al. [6], the lemma's statement is well-defined, as the definition of $\mathrm{RI}(\phi)$ did not change and still includes 0. We proof the lemma by structural induction on the formula ϕ. In this proof $S = (C, R, \iota)$ is a signature, with constants C, predicats R, and the arity function ι. Similarly V is the set of variables. We have the following cases.

- $t \approx t'$, where $t, t' \in V \cup C$. The satisfaction of $t \approx t'$ depends only on the valuation v. Therefore it follows that $(\bar{\mathcal{D}}, \bar{\tau}, v, i) \models t \approx t'$ iff $(\bar{\mathcal{D}}', \bar{\tau}', v, i - c) \models t \approx t'$.
- $t \prec t'$ and $t \preceq$ are analogous to the first one and their detailed proofs are ommitted.
- $r(\bar{(t)})$, where $t_1, \ldots, t_{\iota(r)} \in V \cup C$. Since $(\bar{\mathcal{D}}, \bar{\tau})$ and $(\bar{\mathcal{D}}', \bar{\tau}')$ are $(\mathrm{ERI}(\phi), \mathrm{RI}(\phi), c, i)$-overlapping it follows from Condition 1 in Definition 19 that $\mathrm{filter}(\mathrm{ERI}(\phi), \tau_j, \mathcal{D}_j) = \mathrm{filter}(\mathrm{ERI}(\phi), \tau'_{j-c}\mathcal{D}'_{j-c})$. We make a case distinction on whether $v(\bar{t}) \in r^{\mathcal{D}_i}$, for some time point τ_i. If it is
- $\neg\psi$.
- $\psi \vee \chi$.
- $\exists.\psi$.
- $\bullet_{[a,b)}\psi$.
- $\bigcirc_{[a,b)}$.
- $\psi \, \mathcal{S}_{[a,b)} \, \chi$.
- $\psi \, \mathcal{U}_{[a,b)} \, \chi$.

4.4 Conversion to SQL-Query

Now let's consider how we can convert the extended relative intervals as we have them in Figure 4.3 to a SQL query. On a high level we have one `SELECT` query for each table corresponding to a predicate. The different masks and their relative intervals are appended as conjunctions with a single `WHERE` clause. Let's assume we have a predicate p with $n \in \mathbb{N}$ mask- relative interval tuples, $((m_1, r_1), \ldots (m_n, r_n))$. Variable values in a mask are disregarded. If the constant values in a mask $m_i = (m_{i1}, \ldots, m_{i\iota(p)})$ have the indices $j_1, \ldots, j_l$, with $l \leq \iota(p)$ and the relative interval is $[a, b)$, then the corresponding SQL clause is `WHERE (x<`j_1`> =` m_{ij_1} `AND ... AND x<`j_l`> AND ts >=` a `AND ts <` b`)`. Depending on wheter an interval bound is open or closed, the corresponding comparison operators are used. If an interval is unbounded, then that bound is omitted and all events are retrieved. When multiple masks and intervals for a predicate exist, multiple of the described conditions are concatenated with `AND`. This approach adds potentially overlapping conditions. A good query processor will hopefully recognize those and make optimizations when appropriate. We run every query for each predicate on the database. One additional query is necessary for the `ts` table that gets all time points in the relative interval covering the whole formula. For our example policy in Figure 2.2 with the extended relative intervals as seen in Figure 4.3 and the schema in Figure 2.3.2 we get the following SQL query.

```
FROM loc_accessed SELECT * WHERE (x2 = "advertising" AND
                                  time_stamp >= τ_i − 0 AND
                                  time_stamp <= τ_i − 0)
FROM perm_granted SELECT * WHERE (time_stamp <= τ_i − 0)
FROM perm_revoked SELECT * WHERE (time_stamp <= τ_i − 0)
FROM ts           SELECT * WHERE (time_stamp <= τ_i − 0)
```

Figure 4.2: Extended Relative Intervals of Example Policy

The time stamp is converted to a unix style time stamp string that can be understood by QuestDB [**questdb-time-stamps**]

Chapter 5

Implementation and Evaluation

5.1 Policy Change

This first version of a policy change functions by stopping the current monitor and starting a new one. When starting the new monitor we want to restore the state of the old one. We do this by querying old events from our database. But we do not simply query for the entirety of the database. We make two optimizations. First we use relative intervals and second we make use of constant values. For each predicate occurring in a formula we look for constant attributes in its occurrences. For every predicate and its potential occurrences with different constant values we then compute an over approximation of the relative interval. We use this information to create a SQL query that only queries the constant values combined with the interval. This way we minimize the amount of data that the new monitor has to read and process.

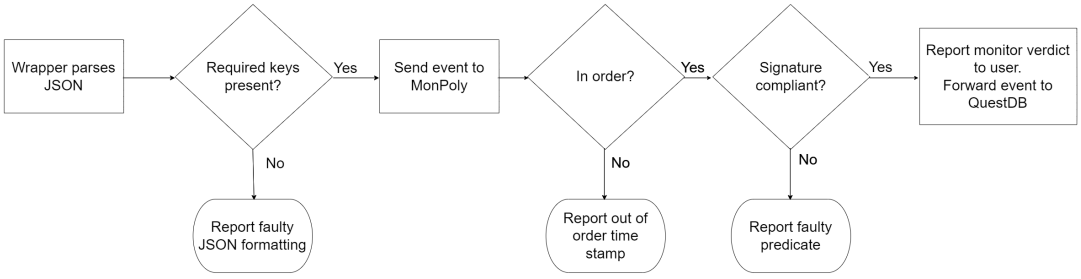

Figure 5.1: Control flow for a new event

Chapter 6

Conclusion

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