A Real-Time, Flexible Logging Infrastructure for MonPoly

Bachelor's Thesis

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Monitoring Problem

- **Runtime Monitoring:** Checking a systems actual behavior against a formal specification
- **Online Monitoring** is done while the system is running
- **Offline Monitoring** is done on a log after a system has completed
- We focus on the Online Monitoring problem

MonPoly

- Runtime Monitor
- Metric First Order Temporal Logic (MFOTL)
- MFOTL temporal operators (left) and syntactic sugar (right)
  - $\bigcirc_I$ ("Next")
  - $\CIRCLE_I$ ("Previous")
  - $\mathcal{U}_I$ ("Until")
  - $\mathcal{S}_I$ ("Since")
  - $\square_I$ ("Always")
  - $\blacksquare_I$ ("Historically")
  - $\lozenge_I$ ("Eventually")
  - $\blacklozenge_I$ ("Once")

  The interval I restricts the time points relevant to an operator.
- Time Point vs. Time Stamp
  - **Time Point**: Time stamped collection of events (predicates), often referred to by an integer index
  - **Time Stamp**: Specifies a moment in time, e.g. seconds since Unix epoch

Time-Series Database

- A time-series database is optimized for the insertion and retrieval of temporal data.
- QuestDB
  - Largely compatible with PostgreSQL
  - Adds a `TIMESTAMP` datatype in addition to the usual types `INT`, `STRING`, etc.
- Dedicated time stamp column (analogous to an index column)

Monitor vs. Database Approach

Monitor (MonPoly)

- Good when:
  - Data changes often
  - Policy changes infrequently
- Bad when:
  - Policy changes frequently

Time-Series Database (QuestDB)

- Good when:
  - Data stays almost constant
  - Varying, frequent queries
- Bad when:
  - Data changes rapidly

Combining Monitoring and Time-Series Database: Motivation

- Build a wrapper that allows for both logging and monitoring on the same data
- Provides the functionality of both monitors and time-series database
- Allows us to offer a policy change method
- More accessible interface
  - Web services
  - Distributed systems
- Increase fault tolerance

Signature to Database Schema

schema.sql

```
CREATE TABLE P(x1 INT,x2 STRING,
               tp INT,
               ts TIMESTAMP)
               timestamp(ts);
CREATE TABLE Q(x1 INT,x2 INT,
               tp INT,
               ts TIMESTAMP)
               timestamp(ts);
CREATE TABLE R(x1 INT,x2 STRING,
               x3 STRING,
               tp INT,
               ts TIMESTAMP)
               timestamp(ts);
CREATE TABLE time_points
               (tp INT,
               ts TIMESTAMP)
               timestamp(ts);
```

signature.sig

```
P(id:int,act:string)
Q(id1:int,id2:int)
R(int,string,string)
```

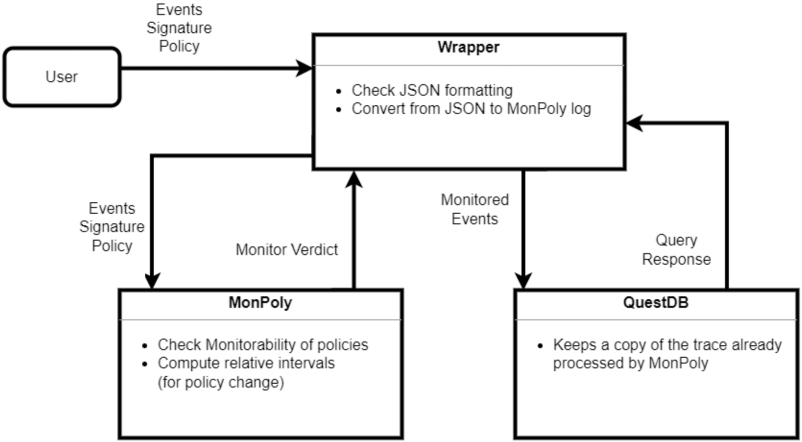
Agenda

- Background and Motivation
  - MonPoly
  - Time-Series Database (QuestDB)
- The Wrapper
  - Architecture
  - Data flow
- Algorithm and Policy Change
  - Relative Intervals
  - Extended Relative Intervals
- Partial Policy Change (Work in Progress)
- Evaluation
  - Overhead of the Wrapper
  - Policy Change Optimization
- Outlook

The Wrapper - REST API

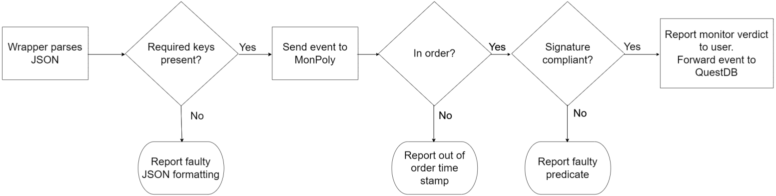
- / (Info-Page)
- `/set-policy`
- `/set-signature`
- `/start-monitor`
- `/stop-monitor`
- `/change-policy`
- `/get-policy`
- `/get-signature`
- `/reset-everything`
- `/log-events`
- `/get-events`
- `/get-most-recent`
- `/db-set-user`
- `/db-set-password`
- `/db-set-host`
- `/db-set-pgsql-port`
- `/db-set-influxdb-port`
- `/db-set-database`
- `/db-get-user`
- `/db-get-password`
- `/db-get-host`
- `/db-get-pgsql-port`
- `/db-get-influxdb-port`
- `/db-get-database`

The Wrapper - Architecture



Data flow

- Increased fault tolerance (compared to MonPoly)



Policy Change

- Start a new monitor with the new policy
- **Goal:** Our monitor evaluates the new policy at the current time point just as if it had seen the same trace as the old monitor
- **Naive approach:** Read entire trace again
- **Idea:** Reduce the size of the trace by removing events that do not influence how the new policy gets evaluated

Optimization Example

$$\phi = (P(x, "a")\, \mathcal{S}_{[0,30)}\, Q(x, 2)) \wedge (\neg(R(y, "c", z))\, \mathcal{S}_{[20,60)}\, P(y, z))$$

- **Relative Interval:** $\mathrm{RI}(\phi) = (-60, 0]$
- **Extended Relative Intervals:** $\mathrm{ERI}(\phi) =$

$$\begin{array}{ll} P(*, *) & \rightarrow (-60, -20] \\ P(*, "a") & \rightarrow (-30, 0] \\ Q(*, 2) & \rightarrow (-30, 0] \\ R(*, "c", *) & \rightarrow (-60, 0] \end{array}$$

- All time points with time stamps not in the interval $\{\text{current time stamp}\} \oplus \mathrm{RI}(\phi)$ do not change the evaluation of ϕ at the current time point.

Interval Operators

Let I and J be two intervals, then

- $I \oplus J = \{i + j \mid i \in I, j \in J\}$
  - $[0, 3] \oplus [-2, 4] = [-2, 7]$
- $I \Cup J$ is the smallest interval that contains all elements that are in at least one of the intervals I and J.
  - $[-4, 1] \Cup [4, 5] = [-4, 5]$

Relative Intervals

Definition

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

$$\begin{cases} \{0\} & \text{atomic formulas} \\ \mathrm{RI}(\psi) & \neg\psi,\ \exists x.\psi, \forall x.\psi \\ \mathrm{RI}(\psi) \Cup \mathrm{RI}(\chi) & \psi \vee \chi, \psi \wedge \chi \\ (-b, 0] \Cup ((-b, -a] \oplus \mathrm{RI}(\psi)) & \CIRCLE_{[a,b)}\psi \\ [0, b) \Cup ([a, b) \oplus \mathrm{RI}(\psi)) & \Circle_{[a,b)} \\ (-b, 0] \Cup ((-b, 0] \oplus \mathrm{RI}(\psi)) \Cup ((-b, -a] \oplus \mathrm{RI}(\chi)) & \psi\, \mathcal{S}_{[a,b)} \chi \\ [0, b) \Cup ([0, b) \oplus \mathrm{RI}(\psi)) \Cup ([a, b) \oplus \mathrm{RI}(\chi)) & \psi\, \mathcal{U}_{[a,b)}\, \chi \end{cases}$$

Basin et al. "Scalable Offline Monitoring of Temporal Specifications". In: *Formal Methods ind System Design 49 (1 2016)*, pp. 75-108

Extended Relative Intervals

Map data structure replaces intervals and new operators are needed. Let M and N be two masked predicate maps and T an interval, then

$$
\begin{aligned}
M \mathbin{\ddot{\Cup}} N = & \{p(I) \to (I \Cup J) \mid p(I) \to I \in m \text{ and } p(I) \to J \in n\} \\
& \cup \{p(I) \to I \mid (p(I) \to I \in m \text{ and } p(I) \in \mathrm{k}(M) \setminus \mathrm{k}(N))\} \\
& \cup \{p(I) \to I \mid (p(I) \to I \in n \text{ and } p(I) \in \mathrm{k}(N) \setminus \mathrm{k}(M))\} \\
T \mathbin{\dot{\Cup}} M = & \{p(I) \to (T \Cup I) \mid p(I) \to I \in M\} \\
T \mathbin{\dot{\oplus}} M = & \{p(I) \to (T \oplus I) \mid p(I) \to I \in M\}
\end{aligned}
$$

Relative Intervals

Definition

The relative interval of the formula ϕ, $\mathsf{RI}(\phi) \subseteq \mathbb{Z}$ is defined inductively over the formula structure: $\mathsf{RI}(\phi) =$

$$
\begin{cases}
\{0\} & \text{atomic formulas} \\
\mathsf{RI}(\psi) & \neg\psi,\ \exists x.\psi, \forall x.\psi \\
\mathsf{RI}(\psi) \Cup \mathsf{RI}(\chi) & \psi \vee \chi, \psi \wedge \chi \\
(-b, 0] \Cup ((-b, -a] \oplus \mathsf{RI}(\psi)) & \CIRCLE_{[a,b)}\psi \\
[0, b) \Cup ([a, b) \oplus \mathsf{RI}(\psi)) & \Circle_{[a,b)} \\
(-b, 0] \Cup ((-b, 0] \oplus \mathsf{RI}(\psi)) \Cup ((-b, -a] \oplus \mathsf{RI}(\chi)) & \psi\, \mathcal{S}_{[a,b)} \chi \\
[0, b) \Cup ([0, b) \oplus \mathsf{RI}(\psi)) \Cup ([a, b) \oplus \mathsf{RI}(\chi)) & \psi\, \mathcal{U}_{[a,b)}\, \chi
\end{cases}
$$

Basin et al. "Scalable Offline Monitoring of Temporal Specifications". In: *Formal Methods ind System Design 49 (1 2016)*, pp. 75-108

Extended Relative Intervals

$$
\mathrm{ERI}(\phi) =
\begin{cases}
\{\} & \text{atomic formulas} \\
 & \text{excl. predicates} \\
\{p(m) \to [0,0]\} & \text{predicate } p \\
 & \text{with mask } m, \\
\mathrm{ERI}(\psi) & \neg\psi, \exists x.\psi, \forall x.\psi \\
\mathrm{ERI}(\psi) \mathbin{\ddot{\cup}} \mathrm{ERI}(\chi) & \psi \vee \chi, \psi \wedge \chi \\
(-b, 0] \mathbin{\dot{\cup}} ((-b, -a] \mathbin{\dot{\oplus}} \mathrm{ERI}(\psi)) & \newmoon_{[a,b)} \psi \\
[0, b) \mathbin{\dot{\cup}} ([a, b) \mathbin{\dot{\oplus}} \mathrm{ERI}(\psi)) & \bigcirc_{[a,b)} \psi \\
(-b, 0] \mathbin{\dot{\cup}} ((-b, 0] \mathbin{\dot{\oplus}} \mathrm{ERI}(\psi)) \mathbin{\ddot{\cup}} ((-b, -a] \mathbin{\dot{\oplus}} \mathrm{ERI}(\chi)) & \psi \, \mathcal{S}_{[a,b)} \, \chi \\
[0, b) \mathbin{\dot{\cup}} ([0, b) \mathbin{\dot{\oplus}} \mathrm{ERI}(\psi)) \mathbin{\ddot{\cup}} ([a, b) \mathbin{\dot{\oplus}} \mathrm{ERI}(\chi)) & \psi \, \mathcal{U}_{[a,b)} \, \chi
\end{cases}
$$

We proofed that this definition is a correct approximation such that it extracts all necessary time points from a trace and that the evaluation of ϕ is the same for the original trace and the extraction.

Extended Relative Intervals - SQL Query

$$\phi = (P(x, "a")\,\mathcal{S}_{[0,30)}\,Q(x, 2)) \wedge (\neg(R(y, "c", z))\,\mathcal{S}_{[20,60)}\,P(y, z))$$

- **Relative Interval:** $\mathrm{RI}(\phi) = (-60, 0]$
- **Extended Relative Intervals:** $\mathrm{ERI}(\phi) =$

$$\begin{aligned}
P(*, *) &\rightarrow (-60, -20] \\
P(*, "a") &\rightarrow (-30, 0] \\
Q(*, 2) &\rightarrow (-30, 0] \\
R(*, "c", *) &\rightarrow (-60, 0]
\end{aligned}$$

Extended Relative Intervals - SQL Query

```
SELECT * FROM P WHERE
    (time_stamp > <NOW>-60 AND time_stamp <= <NOW>-20)
    OR
    (x2 = "a" AND
    time_stamp > <NOW> -30 AND time_stamp <= <NOW>-0);
SELECT * FROM Q WHERE
    (x2 = 2 AND
    time_stamp > <NOW>-30 AND time_stamp <= <NOW>-0);
SELECT * FROM R WHERE
    (x2 = "c" AND
    time_stamp > <NOW>-60 AND time_stamp <= <NOW>-0);
SELECT * FROM time_points WHERE
    (time_stamp > <NOW>-60 AND time_stamp <= <NOW>-0);
```

Database Result Conversion

QuestDB Response


```
[{"R":[]},
{"Q":[[0,8,65536,"Thu, 01 Jan 1970 00:00:01 GMT"]]},
{"P":[]},
{"time_points":[[65536,"Thu, 01 Jan 1970 00:00:01 GMT"],
[65537,"Thu, 01 Jan 1970 00:00:02 GMT"]]}]
```


wrapper.json


```
[{"predicates":[{"name":"Q","occurrences":[[0,8]]}],
"timepoint":65536,"timestamp":"1970-01-01 00:00:01"},
{"predicates":[],
"timepoint":65537,"timestamp":"1970-01-01 00:00:02"}]
```


monpoly.log

```
@1 Q(0,8);
@2 ;
```

Partial Policy Change in MonPoly (Work in Progress)

- Only for **First Order Logic** operators above temporal operators
- **Named formulas:**
  `NAME[f1, name1] OR NAME[f2 and f3, name2]`
- Added *data types* for `NAME` in MonPoly
- Updated *formula parser* for `NAME` constructs
- Started work on commands for adding and removing parts of formulas.
- **Commands** to add or remove conjuncts or disjuncts:

```
>remove_part <name><
>add_conjunct <name1> <name2> <formula><
>add_disjunct <name1> <name2> <formula><
```

Partial Policy Change in MonPoly (Work in Progress)

$$\phi = (P(x, "a") \, \mathcal{S}_{[0,30)} \, Q(x,2)) \wedge (\neg(R(y, "c", z)) \, \mathcal{S}_{[20,60)} \, P(y,z))$$

Becomes:

```
NAME[(P(x,"a") SINCE[0,30) Q(x,2)), part1] AND
NAME[(NOT (R(y,"c",z)) SINCE[20,60) P(y,z)), part2]
```

```
>add_disjunct part1 part3 'NOT P(2,"b")'<
```

```
(NAME[P(x,"a") SINCE[0,30) Q(x,2), part1] OR
NAME[NOT P(2,"b"), part3]) AND
NAME[NOT (R(y,"c",z)) SINCE[20,60) P(y,z), part2]
```

$$\begin{aligned}\phi' = &((P(x, "a") \, \mathcal{S}_{[0,30)} \, Q(x,2)) \wedge (\neg P(2, "b"))) \\ &\wedge (\neg(R(y, "c", z)) \, \mathcal{S}_{[20,60)} \, P(y,z))\end{aligned}$$

Partial Policy Change in MonPoly (Work in Progress)

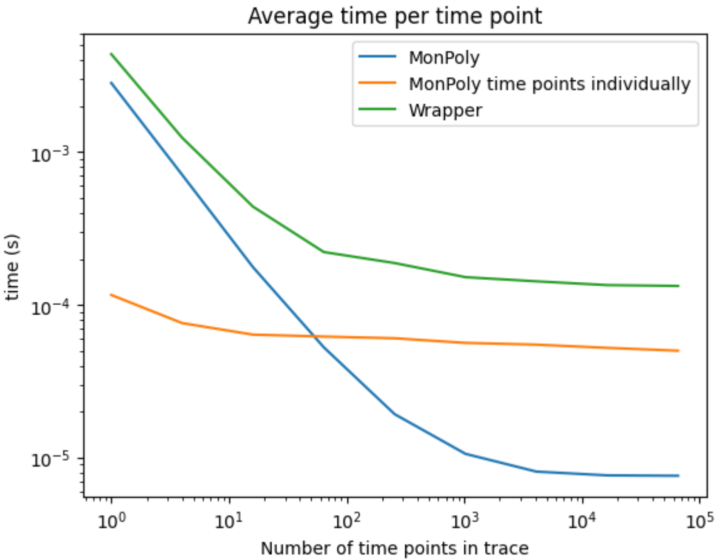
Next up:

- Compute the internal state for formula parts that will be added.
- Combine existing state with the state of the new formula.
- Update state when a formula part gets removed.

Overhead of the Wrapper

- Random policy with intervals bounded by $[0, 20)$
- Random trace with 4^i time points, for $i = 0, \ldots, 8$
- Measure the time it takes for MonPoly to monitor these traces
- Measure the time it takes for MonPoly to monitor the traces, when the time points are not in a single file, but sent individually
  - This is a better simulation of online monitoring
- Measure the time it takes for the wrapper to monitor these traces
- This was done **100 times** (with 100 different policies)

Overhead of the Wrapper



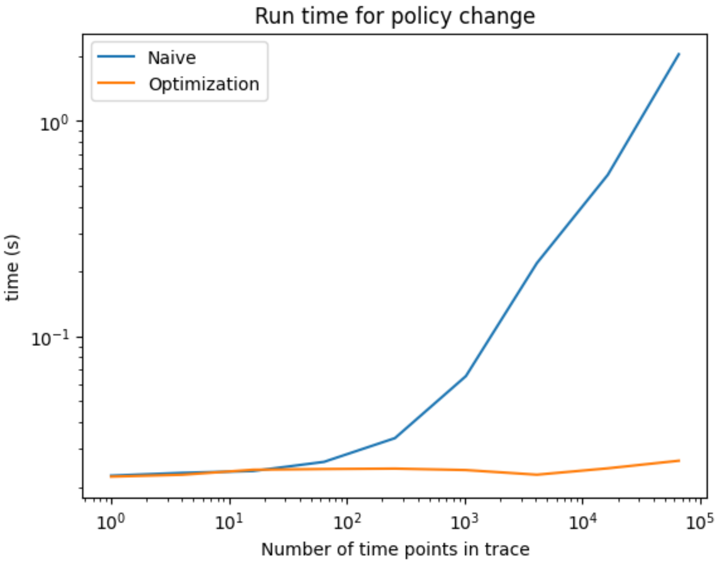
Overhead of the Wrapper - Conclusion

- More detailed profiling is required
- Possible sources of the overhead are:
  - The conversion of our JSON format for logs to the MonPoly format
  - The wrapper sends time points synchronously to MonPoly
  - The wrapper must go over the events once to send them to MonPoly and again later to send them to QuestDB

Policy Change Optimization

- Policy change with 2 randomly generated formulas
- Intervals in policies are bounded by $[0, 20)$.
- Random traces with 4^i time points, for $i = 0, \ldots, 8$
- Load trace into wrapper and then initiate the policy change
- This was done 100 times, for 100 different policy pairs.

Policy Change Optimization



Outlook

- Reduce overhead of the wrapper
  - More in depth profiling of the wrapper
  - Send time points asynchronously (don't wait for response before sending the next time point)
- Speed up policy change
  - More involved checking for constraints on variables in formulas (such as $x < 20$)
- Continue the partial policy change within MonPoly

Thank you for your attention!