MONITORING DECENTRALIZED SPECIFICATIONS

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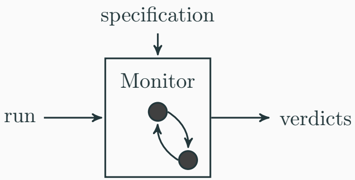
(Decentralized) Monitoring

MONITORING (AKA RUNTIME VERIFICATION) ↪ OVERVIEW

- Lightweight verification technique
- Checks whether a run of a program conforms to a specification (As opposed to model checking which verifies all runs)
- Monitors are synthesized and integrated to observe the system
- Monitors determine a verdict: $\mathbb{B}_3 = \{\top, \bot, ?\}$
  - $\top$ (true): run complies with specification
  - $\bot$ (false): run does not comply with specification
  - ?: verdict cannot be determined (yet)



MONITORING $\hookrightarrow$ SYSTEM ABSTRACTION

1. Components ($\mathcal{C}$)
2. Atomic propositions (AP)
3. Observations/Events ($AP \to \mathbb{B}_2$, possibly partial)
4. Trace: a sequence of events for each component (partial function)

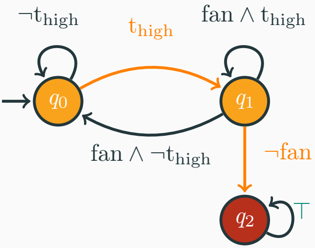
Example

1. $\{c_0, c_1\}$ (Temp sensor + Fan)
2. $\{\mathrm{t}_{\mathrm{low}}, \mathrm{t}_{\mathrm{med}}, \mathrm{t}_{\mathrm{high}}, \mathrm{t}_{\mathrm{crit}}, \mathrm{fan}\}$ (e.g., $\mathrm{t}_{\mathrm{crit}}$ "temperature critical")
3. $\{\langle \mathrm{t}_{\mathrm{low}}, \top\rangle, \langle \mathrm{fan}, \bot\rangle\}$ — "temperature is low and fan is not on"
4. $\begin{bmatrix} 0 \mapsto c_0 & \mapsto \{\langle \mathrm{t}_{\mathrm{low}}, \top\rangle, \langle \mathrm{t}_{\mathrm{med}}, \bot\rangle, \dots\} & 0 \mapsto c_1 & \mapsto \{\langle \mathrm{fan}, \bot\rangle\} \\ 1 \mapsto c_0 & \mapsto \{\langle \mathrm{t}_{\mathrm{med}}, \top\rangle, \dots\} & 1 \mapsto c_1 & \mapsto \{\langle \mathrm{fan}, \bot\rangle\} \\ 2 \mapsto c_0 & \mapsto \{\langle \mathrm{t}_{\mathrm{high}}, \top\rangle, \dots\} & 2 \mapsto c_1 & \mapsto \{\langle \mathrm{fan}, \top\rangle\} \end{bmatrix}$

$$\{\langle \mathrm{t}_{\mathrm{low}}, \top\rangle, \langle \mathrm{fan}, \bot\rangle, \dots\} \cdot \{\langle \mathrm{t}_{\mathrm{med}}, \top\rangle, \langle \mathrm{fan}, \bot\rangle, \dots\} \cdot \{\langle \mathrm{t}_{\mathrm{high}}, \top\rangle, \langle \mathrm{fan}, \top\rangle, \dots\}$$

MONITORING USING AUTOMATA ↪ EXAMPLE

"Fan must always be turned on when temperature is high"



$$\boldsymbol{G}(\mathrm{t_{high}} \implies \boldsymbol{X}\mathrm{fan})$$

1. At $t = 1$, from q_0:

   1.1 Observe

$\mathrm{t_{high}}$	$\top$
fan	$\bot$

   1.2 Eval

$\neg\mathrm{t_{high}}$	$\bot$
$\mathrm{t_{high}}$	$\top$

2. At $t = 2$, from q_1:

   2.1 Observe

$\mathrm{t_{high}}$	$\top$
fan	$\bot$

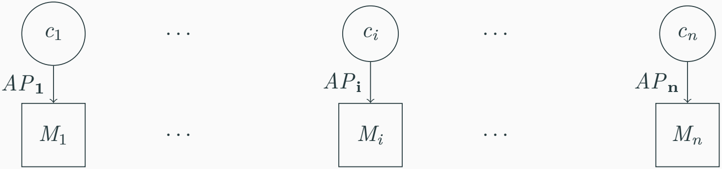
   2.2 Eval

$\mathrm{fan} \wedge \neg\mathrm{t_{high}}$	$\bot$
$\mathrm{fan} \wedge \mathrm{t_{high}}$	$\bot$
$\neg\mathrm{fan}$	$\top$

Monitoring this property requires a central observation point!

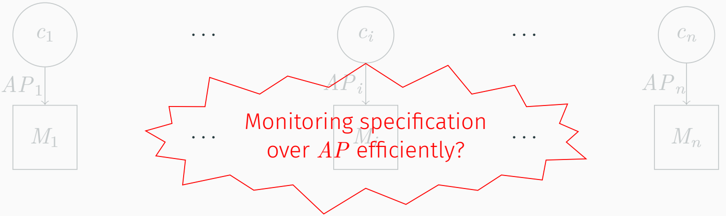
DECENTRALIZED MONITORING ↪ PROBLEM STATEMENT

- General setting
  - $\mathcal{C} = \{c_0, \ldots, c_n\}$: components
  - $AP = AP_0 \cup \ldots \cup AP_n$: atomic propositions, partitioned by $\mathcal{C}$
  - no central observation point
  - but monitors attached to components
- Issues in decentralized monitoring
  - partial views of AP – unknown global state
  - partial execution of the automaton (evaluation)
  - communication between monitors



DECENTRALIZED MONITORING ↪ PROBLEM STATEMENT

- General setting
- Issues in decentralized monitoring
  - partial views of AP – unknown global state
  - partial execution of the automaton (evaluation)
  - communication between monitors
- Existing approaches:
  - based on LTL rewriting — unpredictability of monitor performance
  - all monitors check the same specification — inefficiency



GOALS

Define a methodology of design and evaluation of decentralized monitoring

1. Aim for predictable behavior
   - Move from LTL → Automata
   - Common ground to compare existing (and future) strategies
2. Separate monitor synthesis from monitoring strategies
   - Centralized specification → Decentralized specification
   - Monitorability of a decentralized specification
   - Define a general decentralized monitoring algorithm

★ Extend tooling support for the design methodology

★ Ensure reproducibility

Monitoring with EHEs

Execution History Encoding ↪ Information as Atoms

★ Encode the execution as a datastructure that
  - supports flexibility when receiving partial information
  - is insensitive to the reception order of information
  - has predictable size and operations
- Atomic propositions → Atoms
  - Allow algorithms to add data to observations ($\text{enc} : AP \rightarrow Atoms$)
  - Ordering information (timestamp, round number, vector clock etc.)
- Monitors store Atoms in their Memory
- Monitors need to evaluate $Expr_{Atoms}$
  - rewrite using Memory
  - simplify using Boolean logics (much easier than simplification for LTL)

$$Expr_{Atoms} \times Mem \rightarrow \mathbb{B}_3$$

$$\text{eval}(expr, \mathcal{M}) = \text{simplify}(\text{rw}(expr, \mathcal{M}))$$

$$\text{eval}(\langle 1, \text{t}_{\text{high}} \rangle \wedge \langle 2, \text{fan} \rangle, [\langle 1, \text{t}_{\text{high}} \rangle \mapsto \bot]) = \bot \wedge \langle 2, \text{fan} \rangle = \bot$$

EXECUTION HISTORY ENCODING ↪ AUTOMATA EXECUTION

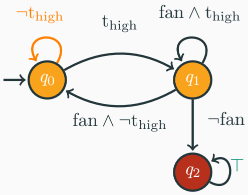
- EHE is a partial function:

$$\mathcal{I} : \mathbb{N} \times Q_{\mathcal{A}} \rightarrow \mathit{Expr}_{\mathit{Atoms}}$$
$$\mathcal{I}(t, q) = \mathit{expr}$$

  - For a given timestamp t
  - The automaton is in state q iff
  - $\mathrm{eval}(\mathit{expr}, \mathcal{M}) = \top$

$$\mathcal{I}(2, q_0) = [\neg\langle 1, \mathrm{t_{high}}\rangle \wedge \neg\langle 2, \mathrm{t_{high}}\rangle] \vee [\langle 1, \mathrm{t_{high}}\rangle \wedge (\langle 2, \mathrm{fan}\rangle \wedge \neg\langle 2, \mathrm{t_{high}}\rangle)]$$

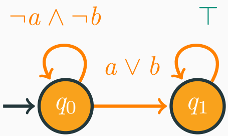
$$\mathrm{eval}(\mathcal{I}(2, q_0), [\langle 1, \mathrm{t_{high}}\rangle \mapsto \bot]) = \mathrm{eval}(\neg\langle 2, \mathrm{t_{high}}\rangle, \ldots) = ?$$



- EHE is constructed recursively and lazily (as needed and on-the-fly) using $\mathcal{A}$

EXECUTION HISTORY ENCODING $\hookrightarrow$ CONSTRUCTION

$$\mathcal{I}^2 = \text{mov}([0 \mapsto q_0 \mapsto \top], 0, 2)$$



t	q	expr
0	q_0	$\top$
1	q_0	$\top \wedge \quad \neg\langle 1, a\rangle \wedge \neg\langle 1, b\rangle$
1	q_1	$\langle 1, a\rangle \vee \langle 1, b\rangle$
2	q_0	$(\neg\langle 1, a\rangle \wedge \neg\langle 1, b\rangle) \wedge (\neg\langle 2, a\rangle \wedge \neg\langle 2, b\rangle)$
2	q_1	$[(\neg\langle 1, a\rangle \wedge \neg\langle 1, b\rangle) \wedge (\langle 2, a\rangle \vee \langle 2, b\rangle)] \vee [(\langle 1, a\rangle \vee \langle 1, b\rangle) \wedge \top]$

$\vdots$

EXECUTION HISTORY ENCODING $\hookrightarrow$ PROPERTIES

1. Soundness (provided that observations can be totally ordered)
    - For the same trace, EHE and $\mathcal{A}$ report the same state
    - → They find the same verdict
2. Strong Eventual Consistency (SEC)
    - We can merge EHEs by disjoining ($\vee$) each entry $\langle t, q \rangle$
    - $\vee$ is commutative, associative and idempotent
    - → EHE is a state-based replicated data-type (CvRDT)
    - → Monitors that exchange their EHE find the same verdict
    - → Can monitor centralized specification shared with multiple monitors
3. Predictable size
    - The EHE encodes all potential and past states, as needed
    - The more we keep track of potential states, the bigger the size
    - → We can assess algorithms by how they manipulate the EHE

EXECUTION HISTORY ENCODING ↪ ANALYSIS

- Information Delay (δ)

  Timestamps needed to expand before determining a state

  Potential states to keep track of

- Size of expression grows with each move beyond t

- Size of EHE:

$$|\mathcal{I}^{\delta}| = \mathcal{O}(\delta|Q|\sum_{1}^{\delta} LP)$$
$$= \mathcal{O}(\delta^{2}|Q|LP)$$

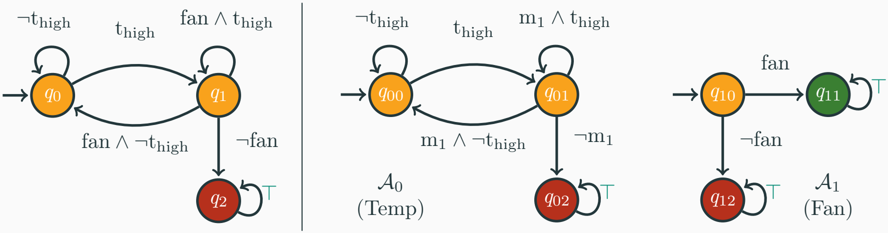
$$t \mapsto q \mapsto \top$$

$$\delta \left\{ \begin{array}{lll}
t+1 \mapsto & \left.\begin{array}{ll} q_0 & \mapsto e_{10} \\ q_1 & \mapsto e_{11} \\ & \vdots \\ q_{|Q|-1} & \mapsto e_{1(|Q|-1)} \end{array}\right\} & |Q| \\
t+2 \mapsto & \left.\begin{array}{ll} q_0 & \mapsto e_{20} \\ & \vdots \\ q_{|Q|-1} & \mapsto e_{2(|Q|-1)} \end{array}\right\} & |Q| \\
\vdots & & \\
t+\delta \mapsto & \left.\begin{array}{ll} q_0 & \mapsto e_{\delta 0} \\ q_1 & \mapsto e_{\delta 1} \\ & \vdots \\ q_{|Q|-1} & \mapsto e_{\delta(|Q|-1)} \end{array}\right\} & |Q|
\end{array}\right.$$

Monitoring Decentralized Specifications

DECENTRALIZED SPECIFICATION

- Each monitor is associated with a tuple $\langle \mathcal{A}, c \rangle$
  - $\mathcal{A}$ is its specification automaton
  - c is the component the monitor is attached to
- The transition labels of an automaton $\mathcal{A}$ are restricted to:
  - Atomic propositions local to the attached component
  - References to other monitors



DECENTRALIZED SPECIFICATION ↪ SEMANTICS & MONITORABILITY

- For an automaton $\mathcal{A}_k$, to evaluate a label m_j at t with a trace tr
  - Run tr starting with t on $\mathcal{A}_j$ starting from q_{j_0}
  - Consider the verdict of the run to be the observation m_j at t

(!) If $\mathcal{A}_j$ never reaches a final verdict we will not be able to monitor $\mathcal{A}_k$

(?) Monitorability: "From any state in $\mathcal{A}_k$, we can reach a final verdict"

- $\mathrm{monitorable}(\mathcal{A}_k)$ iff $\forall q \in Q_{\mathcal{A}_k}, \exists q_f \in Q_{\mathcal{A}_k}, \exists e_f \in \mathrm{paths}(q, q_f)$, s.t.
  1. Path can be taken: e_f is satisfiable;
  2. Path leads to a verdict: $\mathrm{ver}_k(q_f) \in \{\bot, \top\}$;
  3. All its dependencies are monitorable:

     $\forall \mathrm{m}_j \in \mathrm{dep}(e_f)$: $\mathrm{monitorable}(\mathcal{A}_j)$.

- Expressions that determine paths between states (n = path length)
  - $\mathrm{paths}(q_s, q_e) = \left\{ \mathtt{expr} \;\middle|\; \begin{array}{l} \exists n \in \mathbb{N} : \mathcal{I}^n(n, q_e) = \mathtt{expr} \\ \wedge\, \mathcal{I}^n = \mathrm{mov}([0 \mapsto q_s \mapsto \top], 0, n) \end{array} \right\}$

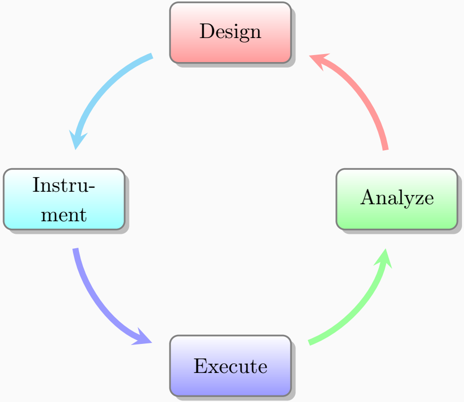
GENERALIZED MONITORING ALGORITHM ↪ OVERVIEW

1. Setup (Deploy)
   - 1.1 Analyze and convert the specification as necessary
   - 1.2 Create monitors, and assign them a specification
     - (!) The monitor handles encoding of AP and Memory
   - 1.3 Attach monitors to components

2. Monitoring
   - 2.1 Wait to receive observations from attached component
   - 2.2 Receive messages (EHE) from monitors
   - 2.3 Process observations and messages (update the local EHE)
   - 2.4 Communicate with other monitors

The THEMIS Approach

THEMIS ↪ Overview



Step	Description
Design	Design a monitoring algorithm
Instru-ment	Create or re-use metrics. Metrics are automatically instrumented using AspectJ
Execute	Use `THEMIS` tools to execute one or more monitoring run(s)
Analyze	Measures are stored in a database for postmortem analysis

Setup

```java
Map<Integer, ? extends Monitor> setup() {
  config.getSpec().put("root",
      Convert.makeAutomataSpec(
        config.getSpec().get("root")));
  Map<Integer, Monitor> mons = new HashMap<Integer, Monitor>();
  Integer i = 0;
  for(Component comp : config.getComponents()) {
    MonMigrate mon = new MonMigrate(i);
    attachMonitor(comp, mon);
    mons.put(i, mon);
    i++;
  }
  return mons;
}
```

Monitor

```java
void monitor(int t, Memory<Atom> observations)
throws ReportVerdict, ExceptionStopMonitoring {
    m.merge(observations);
    if(receive()) isMonitoring = true;
    if(isMonitoring) {
      if(!observations.isEmpty())
        ehe.tick();
      boolean b = ehe.update(m, -1);
      if(b) {
        VerdictTimed v = ehe.scanVerdict();
        if(v.isFinal())
          throw new ReportVerdict(v.getVerdict(), t);
        ehe.dropResolved();
      }
      int next  = getNext();
      if(next != getID()) {
        Representation toSend = ehe.sliceLive();
        send(next, new RepresentationPacket(toSend));
        isMonitoring = false;
      }
    }
  }
```

EXAMPLES ↪ METRICS

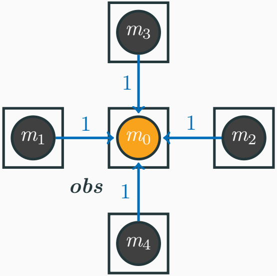
```
void setupRun(MonitoringAlgorithm alg) {
 addMeasure(new Measure("msg_num","Msgs",0L,Measures.addLong));
}
after(Integer to, Message m) : Commons.sendMessage(to, m) {
 update("msg_num" , 1L);
}
```

```
SELECT alg, comps, avg(msg_num), avg(msg_data), count(*)
FROM bench WHERE alg in ('Migration', 'MigrationRR')
GROUP BY alg, comps
```

	alg	comps	avg(msg_num)	avg(msg_data)	count(*)
1	Migration	3	2.04226336011177	267.8458714635	572600
2	Migration	4	2.16402472527473	668.129401098901	364000
3	Migration	5	3.33806822465134	3954.09705050886	530600
4	MigrationRR	3	32.7222301781348	482.572275585051	572600
5	MigrationRR	4	31.8533351648352	932.708425824176	364000
6	MigrationRR	5	19.2345269506219	4361.30746324915	530600

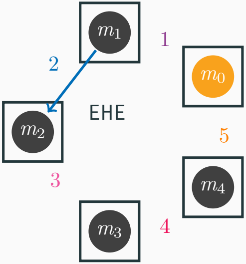
EXISTING ALGORITHMS

STUDYING EXISTING ALGORITHMS ↪ EXPECTED BEHAVIOR



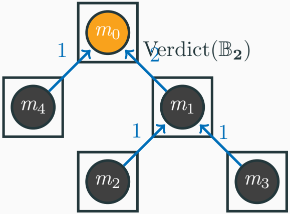
Orchestration

- δ is constant
- #Msgs is linear in components
- |Msg| constant: observations per component



Migration

- δ is linear in components
- #Msgs is constant
- |Msg| is size of EHE: $\mathcal{O}(\delta^2)$, quadratic in components



Choreography

- δ is linear in network depth (algorithm)
- #Msgs is linear in network edges
- |Msg| is constant

#Msgs and |Msg| are predicted on a per round basis

Conclusions

SUMMARY AND FUTURE WORK

⋆ Decentralized Monitoring of (De)Centralized Specifications

1. Aim for predictable behavior → Automata + EHE data structure
2. Separate synthesis from monitoring: decentralized specifications
3. Methodology + tool support for designing, measuring, comparing and extending decentralized RV algorithms
4. Adapted and compared existing algorithms

⋆ Future Work

1. Centralised specification → equivalent decentralized specifications
    - Optimize existing methods
    - Take into account topology of the monitored system
2. Extend THEMIS
    - New metrics
    - Support a fully-asynchronous monitoring approach
    - Better visualization of (the behavior of) algorithms
3. Runtime enforcement of centralized and decentralized specifications

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