MONITORING DECENTRALIZED SPECIFICATIONS

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(overview of joint work with A. Bauer, C. Colombo, and A. El-Hokayem)

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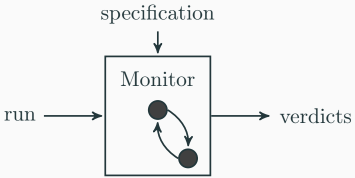
MONITORING (AKA RUNTIME VERIFICATION) $\hookrightarrow$ OVERVIEW

- Lightweight verification technique
- Checks whether a run of a (blackbox) 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)



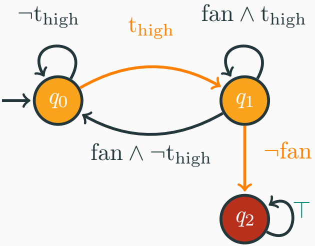
1. Components ($\mathcal{C}$)
2. Atomic propositions (AP)
3. Observations/Events ($AP \rightarrow \mathbb{B}_2$, possibly partial)
4. Trace: a sequence of events for each component (partial function)

Example

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

$$\{\langle \mathrm{t_{low}}, \top\rangle, \langle \mathrm{fan}, \bot\rangle, \ldots\} \cdot \{\langle \mathrm{t_{med}}, \top\rangle, \langle \mathrm{fan}, \bot\rangle, \ldots\} \cdot \{\langle \mathrm{t_{high}}, \top\rangle, \langle \mathrm{fan}, \top\rangle, \ldots\}$$

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



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

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

   1.1 Observe

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

   1.2 Eval

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

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

   2.1 Observe

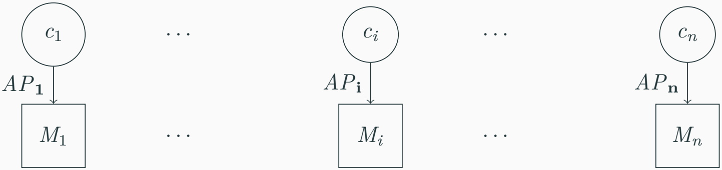
t_{high}	$\top$
fan	$\bot$

   2.2 Eval

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

Monitoring this property requires a central observation point!

- 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
- Challenges:
  - partial views of AP – unknown global state
  - partial execution of the monitor (evaluation)
  - communication between and organisation of monitors



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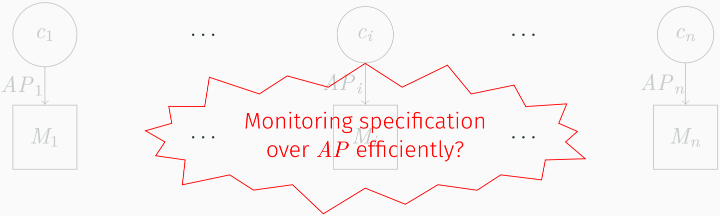
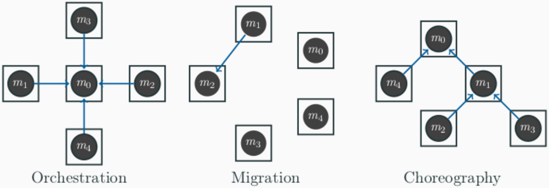


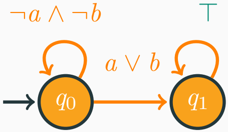
RESULTS

A methodology of design and evaluation of decentralized monitoring

1. Predictable monitor behavior
    - Specifications in LTL or as Automata
    - Data-structure: Execution History Encoding (EHE)
2. Separated monitor synthesis from monitoring strategies
    - Centralized specification → Decentralized specification
        - Monitors can now focus on parts of the specification
        - Monitors communicate with other monitors (explicitly)
    - Topologies of monitors (and dependencies)



3. THEMIS tool for the design and (reproducible) evaluation of decentralised monitoring algorithms



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	$[(\neg\langle 1, a\rangle \wedge \neg\langle 1, b\rangle) \wedge (\langle 2, a\rangle \vee \langle 2, b\rangle)] \vee [(\langle 1, a\rangle \vee \langle 1, b\rangle) \wedge \top]$

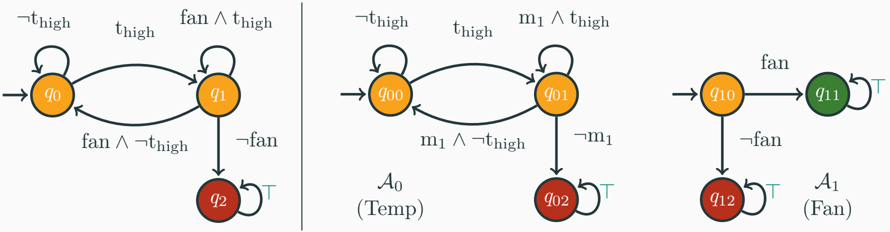
$\vdots$

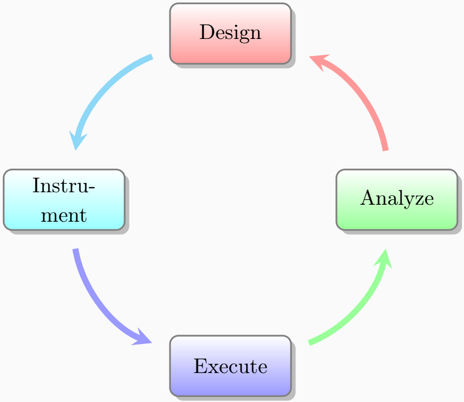
1. Soundness (provided that observations can be totally ordered)
   - For the same trace, EHE and $\mathcal{A}$ report the same state/verdict
2. Strong Eventual Consistency (SEC)
   - EHE is a state-based replicated data-type (CvRDT)
   - → Order of messages does not effect the outcome
   - → Monitors that exchange their EHE find the same verdict
3. Predictable size
   - The EHE encodes all potential and past states, as needed
   - → Can assess the complexity of algorithms by how they manipulate EHE

Algorithm	delay	# Msg	|Msg|
Orchestration	$\Theta(1)$	$\Theta(\|\mathcal{C}\|)$	$O(\|AP_c\|)$
Migration	$O(\|\mathcal{C}\|)$	$O(m)$	$O(m\|\mathcal{C}\|^2)$
Choreography	$O(\mathrm{depth}(\mathrm{m_{root}}))$	$\Theta(\|E\|)$	$\Theta(1)$

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
- Formal semantics and underlying issues in papers :-)





- **Design**: Design a monitoring algorithm
- **Instrument**: 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

Use a common API to build algorithms and measures

(1) Design (monitoring algorithms)

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;
      }
    }
  }
```

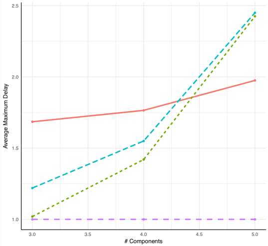
(2) Instrument (# msg)

```java
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);
}
```

(3) Execute (simulation) and (4) Analyze

```sql
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



SUMMARY AND FUTURE WORK

- ⋆ Decentralized Monitoring of (De)Centralized Specifications
  1. Aim for predictable behavior → EHE data structure
  2. Separate synthesis from monitoring → decentralized specifications
  3. Methodology + tool support for designing, measuring, comparing and extending decentralized RV algorithms → THEMIS tool

`https://gitlab.inria.fr/monitoring/themis-demo`

- ⋆ Future/Ongoing Work
  1. Centralised specification → equivalent decentralized specifications
  2. Runtime enforcement of centralized and decentralized specifications
  3. Home Automation systems on iCasa with G. Vega and P. Lalanda
     - How to write clear, scalable, and modular specifications?
     - How to efficiently organize monitors?
     - How to manage interactions (and conflicts) between monitors?

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