ON THE MONITORING OF DECENTRALIZED SPECIFICATIONS

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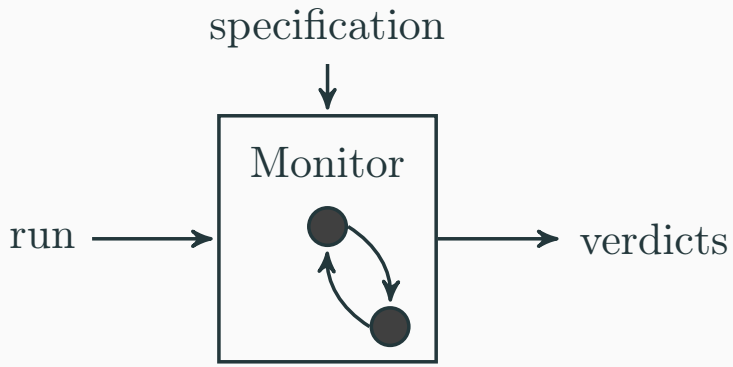
Based on joint recent work with Antoine El-Hokayem to appear in ACM TOSEM and some earlier work with Andreas Bauer and Cristian Colombo in Springer FMSD.

(Decentralized) Monitoring

MONITORING (AKA RUNTIME VERIFICATION) ↪ OVERVIEW

- Lightweight verification technique.
- Checks whether a run of a program conforms to a specification. (Incomplete, as opposed to exhaustive verification techniques.)
- Specification is formalized.
- Monitors are synthesized and integrated to observe the system.
- Monitors determine a verdict in $\mathbb{B}_3 = \{\top, \bot, ?\}$:
  - $\top$ (true): run complies with specification
  - $\bot$ (false): run does not comply with specification
  - ? (undetermined): 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 ($\mathbb{N} \to \mathcal{C} \to AP \to \mathbb{B}_2$)

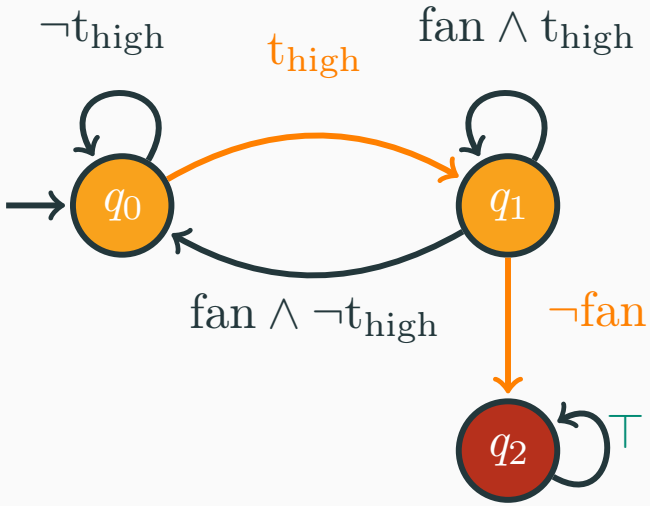
Example

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. $$\begin{bmatrix} 0 \mapsto c_0 & \mapsto \{\langle \mathrm{t}_{\mathrm{low}}, \top \rangle, \langle \mathrm{t}_{\mathrm{med}}, \bot \rangle, \ldots\} & 0 \mapsto c_1 & \mapsto \{\langle \mathrm{fan}, \bot \rangle\} \\ 1 \mapsto c_0 & \mapsto \{\langle \mathrm{t}_{\mathrm{med}}, \top \rangle, \ldots\} & 1 \mapsto c_1 & \mapsto \{\langle \mathrm{fan}, \bot \rangle\} \\ 2 \mapsto c_0 & \mapsto \{\langle \mathrm{t}_{\mathrm{high}}, \top \rangle, \ldots\} & 2 \mapsto c_1 & \mapsto \{\langle \mathrm{fan}, \top \rangle\} \end{bmatrix}$$

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

MONITORING USING AUTOMATA ↪ EXAMPLE

"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	$\bot$

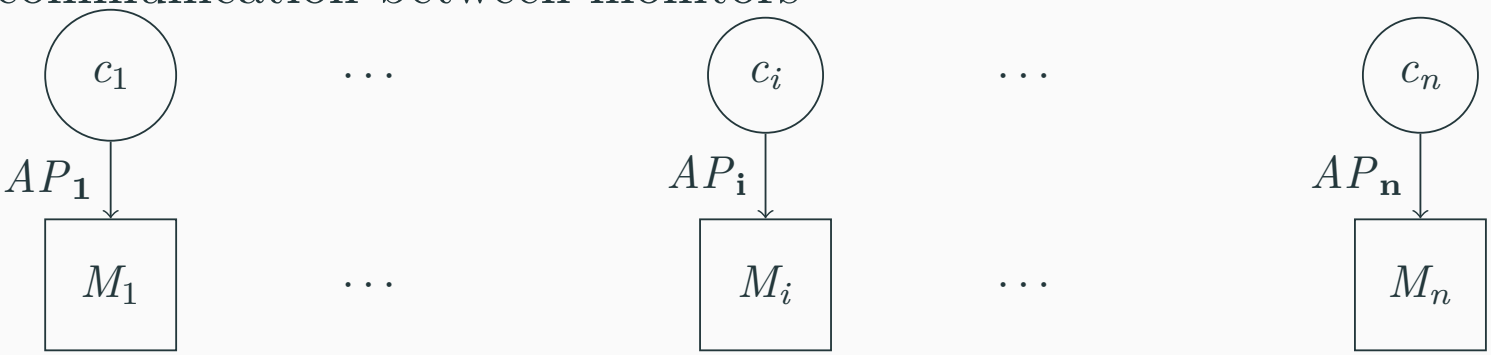
   - 2.2 Eval

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

Monitoring this property requires a central observation point!

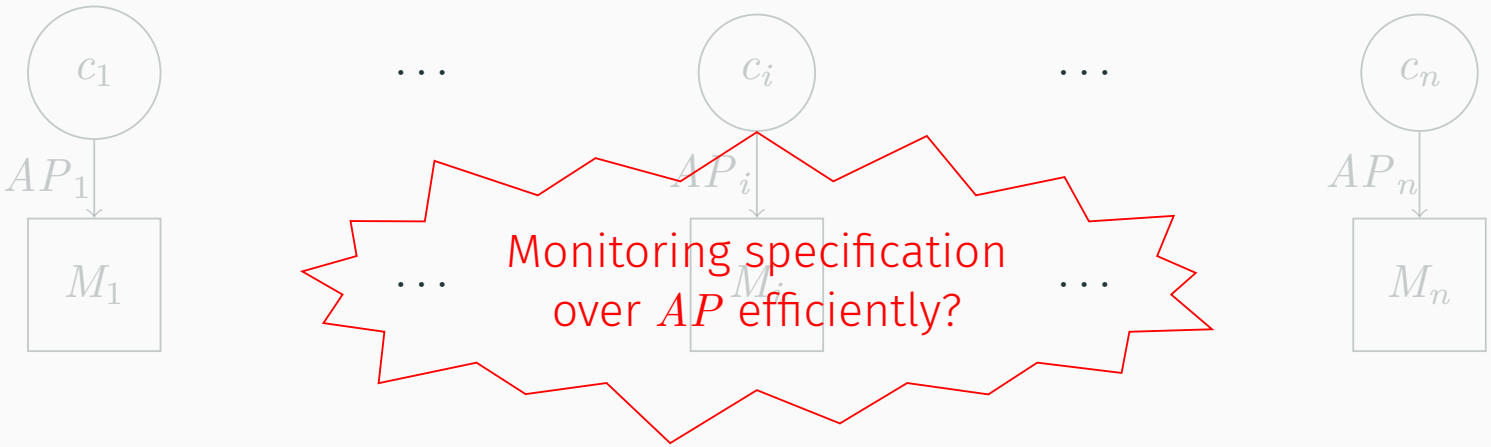
DECENTRALIZED MONITORING ↪ PROBLEM STATEMENT

- 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.

(Decentralized) Monitoring

Monitoring with EHEs

Monitoring Decentralized Specifications

The THEMIS Approach

Experiments

Bringing Runtime Verification Home

Conclusions

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 (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)

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

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

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

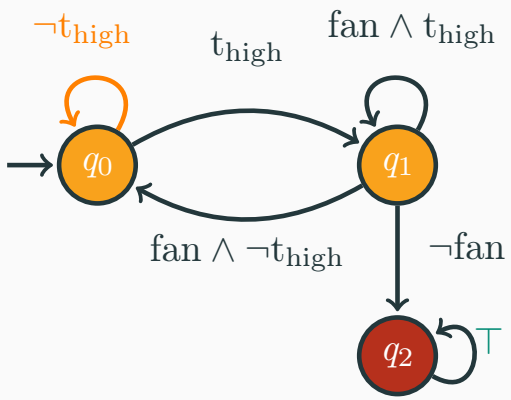
EXECUTION HISTORY ENCODING $\hookrightarrow$ AUTOMATA EXECUTION

- EHE is a partial function:

$$\mathcal{I} : \mathbb{N} \times Q_{\mathcal{A}} \to Expr_{Atoms}$$
$$\mathcal{I}(t, q) = expr$$

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

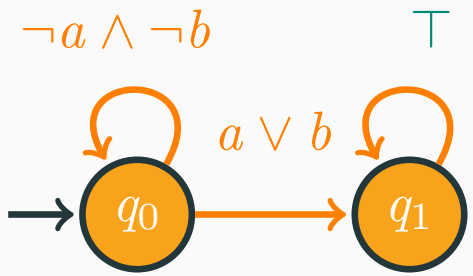
$$\mathcal{I}(2, q_0) = [\neg\langle 1, \text{t}_{\text{high}}\rangle \wedge \neg\langle 2, \text{t}_{\text{high}}\rangle]$$
$$\vee\, [\langle 1, \text{t}_{\text{high}}\rangle \wedge (\langle 2, \text{fan}\rangle \wedge \neg\langle 2, \text{t}_{\text{high}}\rangle)]$$
$$\text{eval}(\mathcal{I}(2, q_0), [\langle 1, \text{t}_{\text{high}}\rangle \mapsto \bot])$$
$$= \text{eval}(\neg\langle 2, \text{t}_{\text{high}}\rangle, \ldots) = ?$$



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

EXECUTION HISTORY ENCODING ↪ CONSTRUCTION

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



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 ↪ 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
   - 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) [Shapiro].

   → 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 $\hookrightarrow$ ANALYSIS

- Information delay (δ):
  - expanded timestamps with no state determined;
  - potential states to keep track of.
- Size of expressions grows with each move beyond t.
- Size of one expression $S(t')$, $t' > t$:

$$S(t') = |Q| \times (S(t'-1) + L)$$
$$= \mathcal{O}(|Q|^{t'}).$$

- Size of EHE:

$$|\mathcal{I}^{\delta}| = \mathcal{O}\left(\delta \times |Q| \times L \times |Q|^{\delta}\right).$$

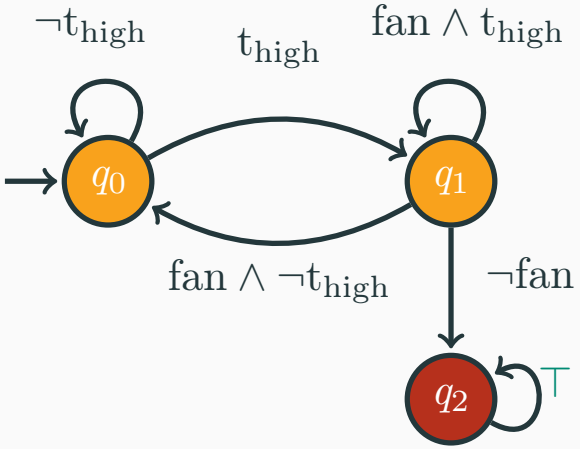
$$t \mapsto q \mapsto \top$$

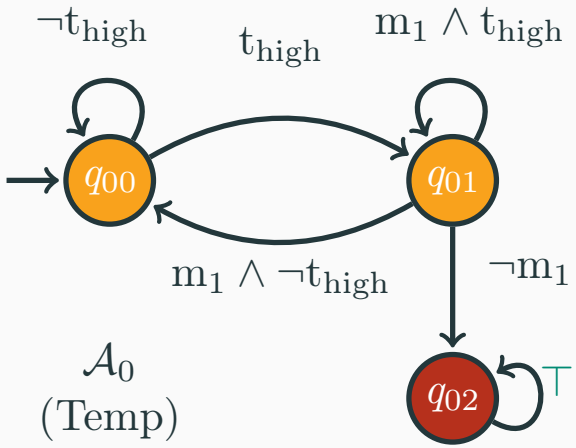
$$\delta \begin{cases} t+1 \mapsto \begin{cases} q_0 \mapsto e_{10} \\ q_1 \mapsto e_{11} \\ \vdots \\ q_{|Q|-1} \mapsto e_{1(|Q|-1)} \end{cases} & |Q| \\ t+2 \mapsto \begin{cases} q_0 \mapsto e_{20} \\ \vdots \\ q_{|Q|-1} \mapsto e_{2(|Q|-1)} \end{cases} & |Q| \\ \vdots \\ t+\delta \mapsto \begin{cases} q_0 \mapsto e_{\delta 0} \\ q_1 \mapsto e_{\delta 1} \\ \vdots \\ q_{|Q|-1} \mapsto e_{\delta(|Q|-1)} \end{cases} & |Q| \end{cases}$$

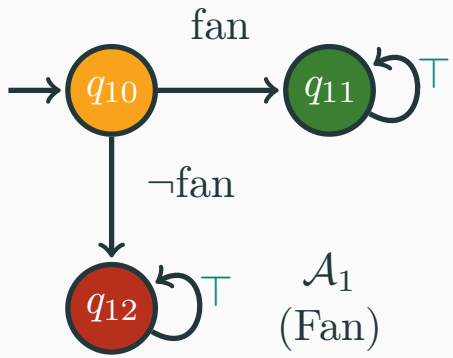
Monitoring Decentralized Specifications

DECENTRALIZED SPECIFICATIONS

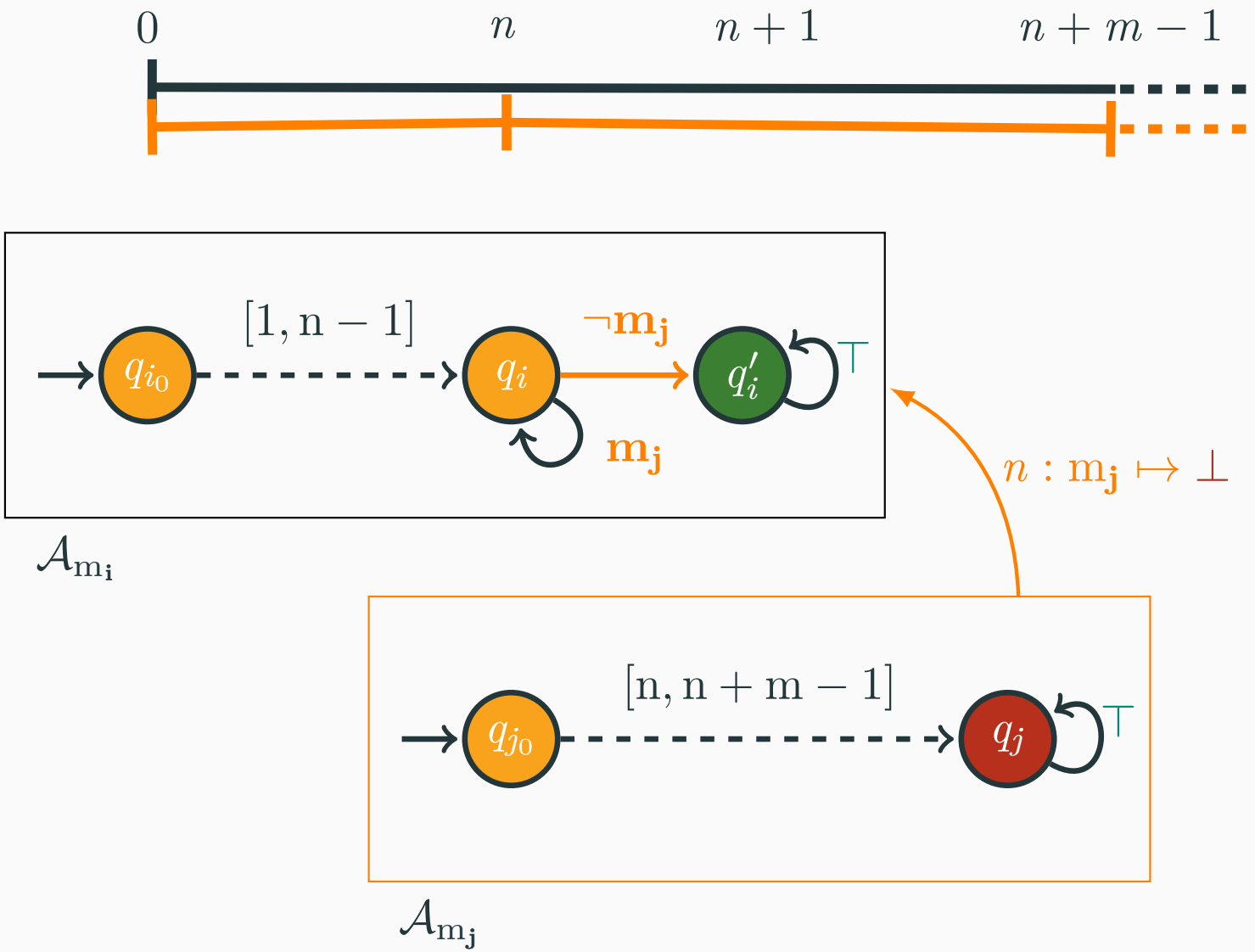
- A single automaton → Set of automata/monitors (Mons).
- Each monitor is associated with a component ($\mathcal{L} : \text{Mons} \to \mathcal{C}$).
- Set of references to monitors (atomic propositions) (AP_{mons})
- The transition labels of an automaton $m \in \text{Mons}$ are restricted to:
  - Atomic propositions local to the attached component ($\mathcal{L}(m)$).
  - References to other monitors.







DECENTRALIZED SPECIFICATIONS ↪ EVALUATING REFERENCES/SEMANTICS



★ Managing buffering and potential states using EHE.

PROPERTIES OF DECENTRALIZED SPECIFICATIONS ↪ MONITORABILITY

- Monitorability: "Is a given specification monitorable?"
- Non-monitorable $\implies$ monitors will never yield a verdict
- [Pnueli] For any (finite) trace t, does there exist a continuation t' s.t. $t \cdot t'$ yields a final verdict?
- Monitorability of automata: are all states co-reachable to states labeled by final verdicts?
  - Necessary & sufficient
  - Decidable in $\mathcal{O}(|Q| + |\delta|)$ time (quadratic in $|Q|$ worst-case).
- Decentralized specification: needs to account for dependencies.
  1. Every automaton must be monitorable; and
  2. Graph of monitor dependencies has no cycle.
  3. Decidable: cycle detection (monitor dependency graph, DFS/SCC)
  4. This is (only) a sufficient condition.
     (boolean simplification can eliminate dependencies: $\mathrm{s} \vee \mathrm{m}_1$)

GENERAL MONITORING ALGORITHM ↪ OVERVIEW

- Generalizes existing algorithms for decentralized monitoring of LTL/automata specifications.
- 2 stages: setup and monitoring.

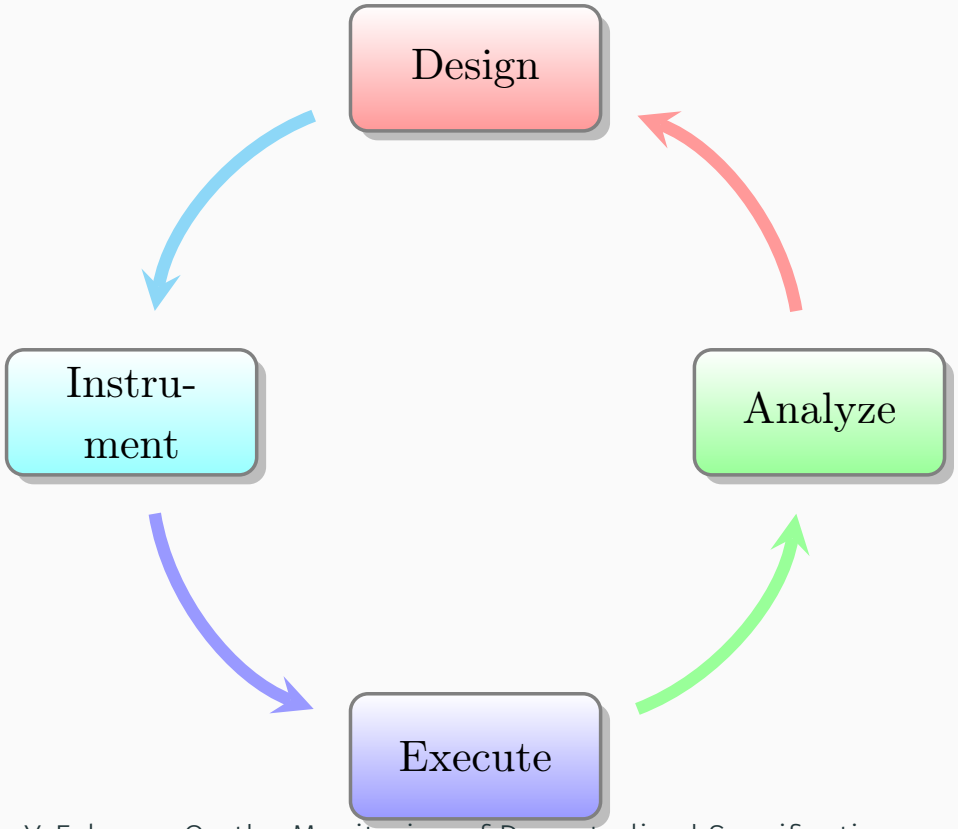
1. Setup (Deploy)
   - 1.1 Analyze and convert the specification as necessary.
   - 1.2 Create monitors and assign them a specification.
     - (!) The monitor handles encoding of AP and Memory.
   - 1.3 Attach monitors to components.
2. Monitoring
   - 2.1 Wait to receive observations from attached component.
   - 2.2 Receive messages (EHE or verdicts) from monitors.
   - 2.3 Process observations and messages (update the local EHE).
   - 2.4 Communicate with other monitors.

The THEMIS Approach

THEMIS ↪ Overview

Java and AspectJ implementation (5,700 LOC).

- Library: all necessary building blocks to develop, simulate, instrument, and execute decentralized algorithms.
- Command-line tools: basic functionality to generate traces, execute a monitoring run and execute a full experiment (multiple parametrized runs).



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

```
1  Map<Integer, ? extends Monitor>
   ↪  setup() {
2    config.getSpec().put("root",
3        Convert.makeAutomataSpec(
4          config.getSpec().get("root")));
5    Map<Integer, Monitor> mons = new
     ↪  HashMap<Integer, Monitor>();
6    Integer i = 0;
7    for(Component comp :
     ↪  config.getComponents()) {
8      MonMigrate mon = new
       ↪  MonMigrate(i);
9      attachMonitor(comp, mon);
10     mons.put(i, mon);
11     i++;
12   }
13   return mons;
14 }
```

Monitor

```
1  void monitor(int t, Memory<Atom> observations)
2  throws ReportVerdict, ExceptionStopMonitoring {
3      m.merge(observations);
4      if(receive()) isMonitoring = true;
5      if(isMonitoring) {
6        if(!observations.isEmpty())
7          ehe.tick();
8        boolean b = ehe.update(m, -1);
9        if(b) {
10         VerdictTimed v = ehe.scanVerdict();
11         if(v.isFinal())
12           throw new
             ↪  ReportVerdict(v.getVerdict(), t);
13         ehe.dropResolved();
14       }
15       int next  = getNext();
16       if(next != getID()) {
17         Representation toSend = ehe.sliceLive();
18         send(next, new
           ↪  RepresentationPacket(toSend));
19         isMonitoring = false;
20       }
21     }
22   }
```

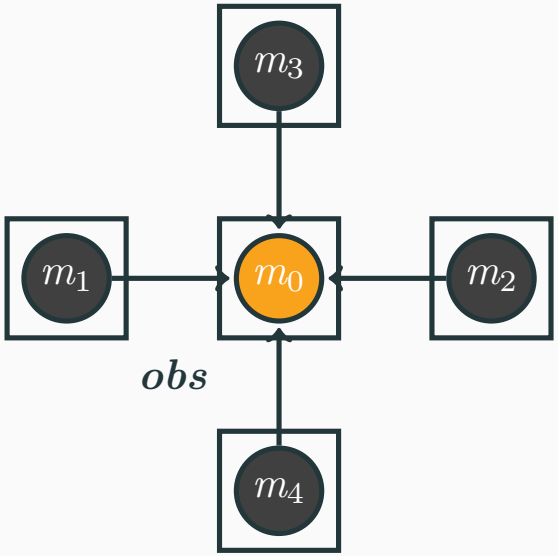
EXAMPLES ↪ METRICS

```
1 void setupRun(MonitoringAlgorithm alg) {
2  addMeasure(new Measure("msg_num","Msgs",0L,Measures.addLong));
3 }
4 after(Integer to, Message m) : Commons.sendMessage(to, m) {
5  update("msg_num" , 1L);
6 }
```

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

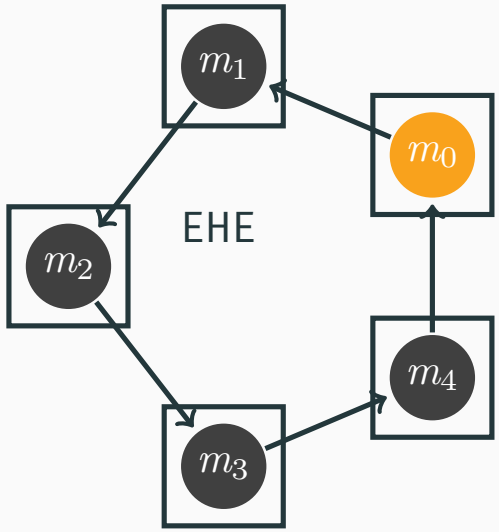
	alg	comps	avg(msg_num)	avg(msg_data)	count(*)
1	Migration	3	2.04226336011177	267.8458714635	572600
2	Migration	4	2.16402472527473	668.129401098901	364000
3	Migration	5	3.33806822465134	3954.09705050886	530600
4	MigrationRR	3	32.7222301781348	482.572275585051	572600
5	MigrationRR	4	31.8533351648352	932.708425824176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

STUDYING EXISTING ALGORITHMS ↪ PRINCIPLES OF THE ALGORITHMS



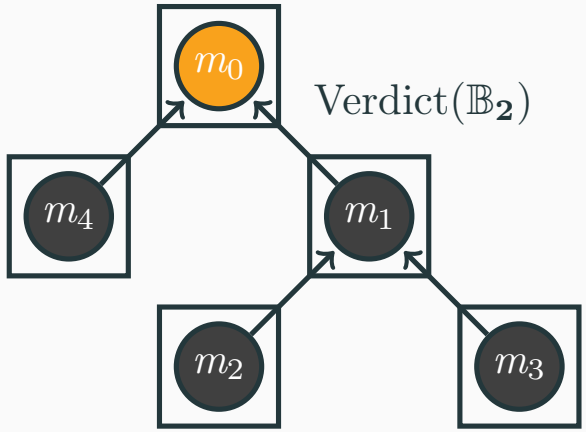
Orchestration

- one central monitor
- observations are forwarded to the central monitor



Migration

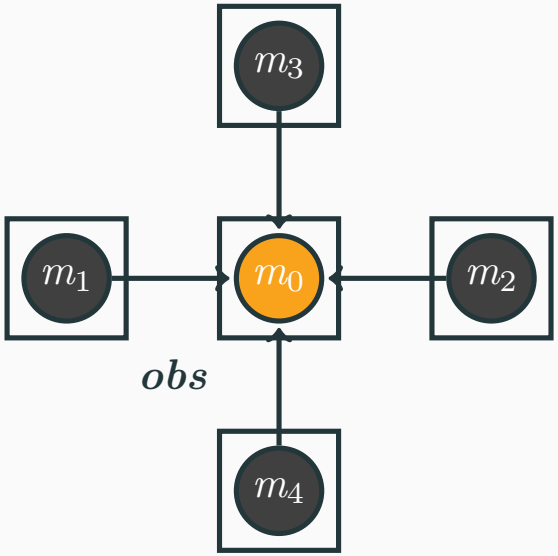
- monitor state “hops"
- monitor updates it with local information
- forward to the next monitor

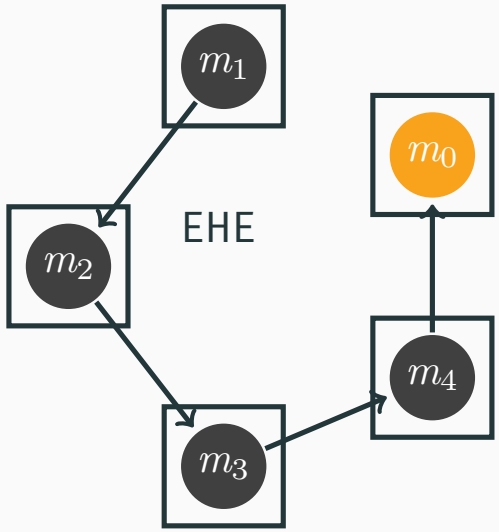


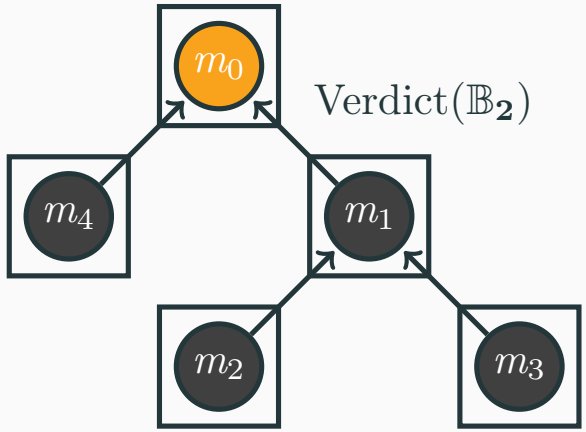
Choreography

- DAG of monitors
- a monitor evaluates a sub-specification
- verdict propagates in the DAG

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: exponential in components

Choreography

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

EXISTING ALGORITHMS

GraphStream

LIG cnrs Inria Université Grenoble Alpes

Experiments

Studying existing algorithms ↪ Verifying Behavior

Simulate the behavior of orchestration, migration, and choreography.

Confirm the trends predicted by the analysis.

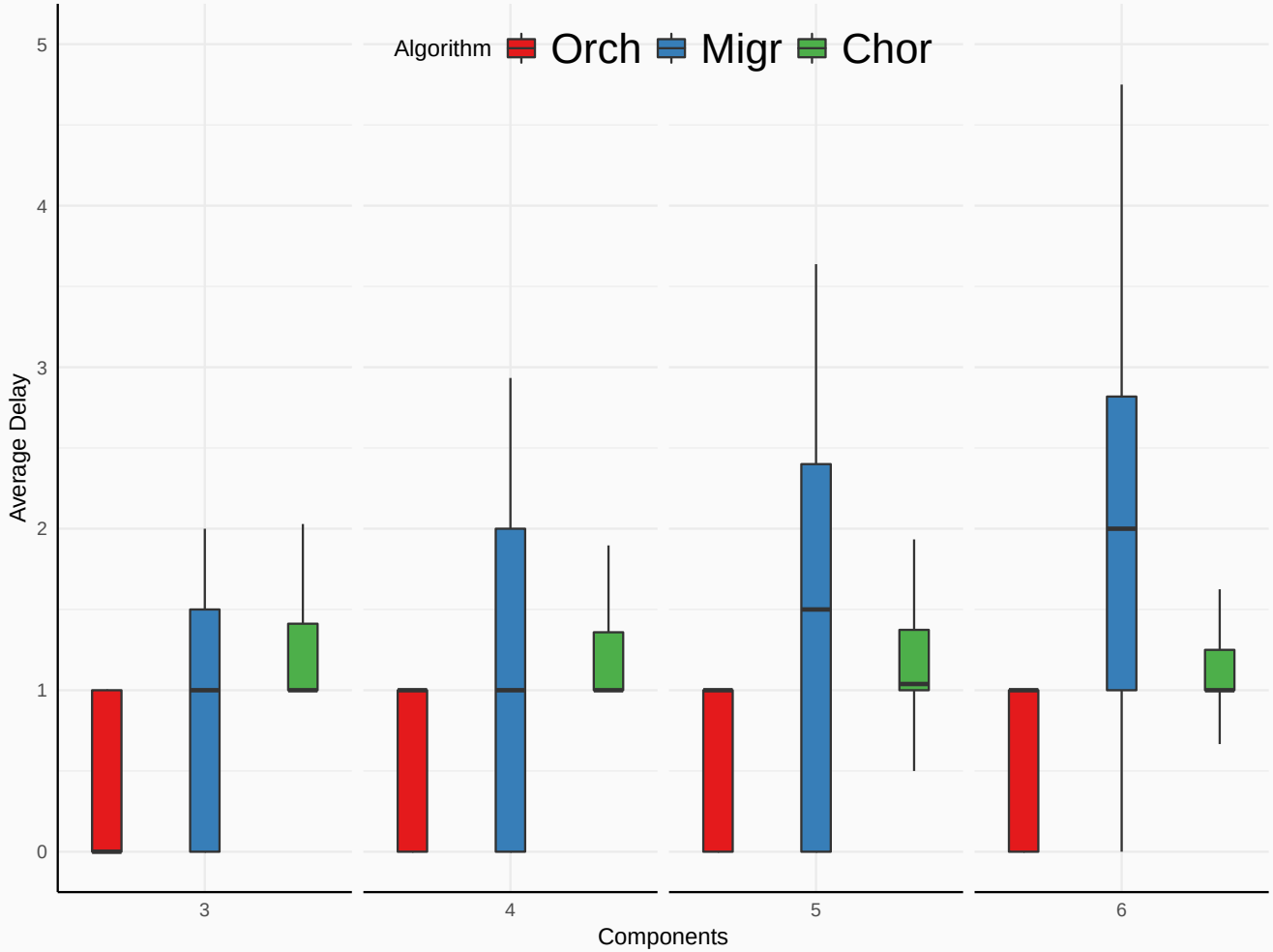
Experiment Setup ($5,868,800$ runs): [1]

- 200 synthetic random traces of 100 events (2 observations/component).
- Vary $|\mathcal{C}|$ from 3 to 5.
- At least 1,000 random specifications per scenario.

[1] More experiments and results in paper:

- several probability distributions for events,
- more metrics,
- a case study on the Chiron UI.

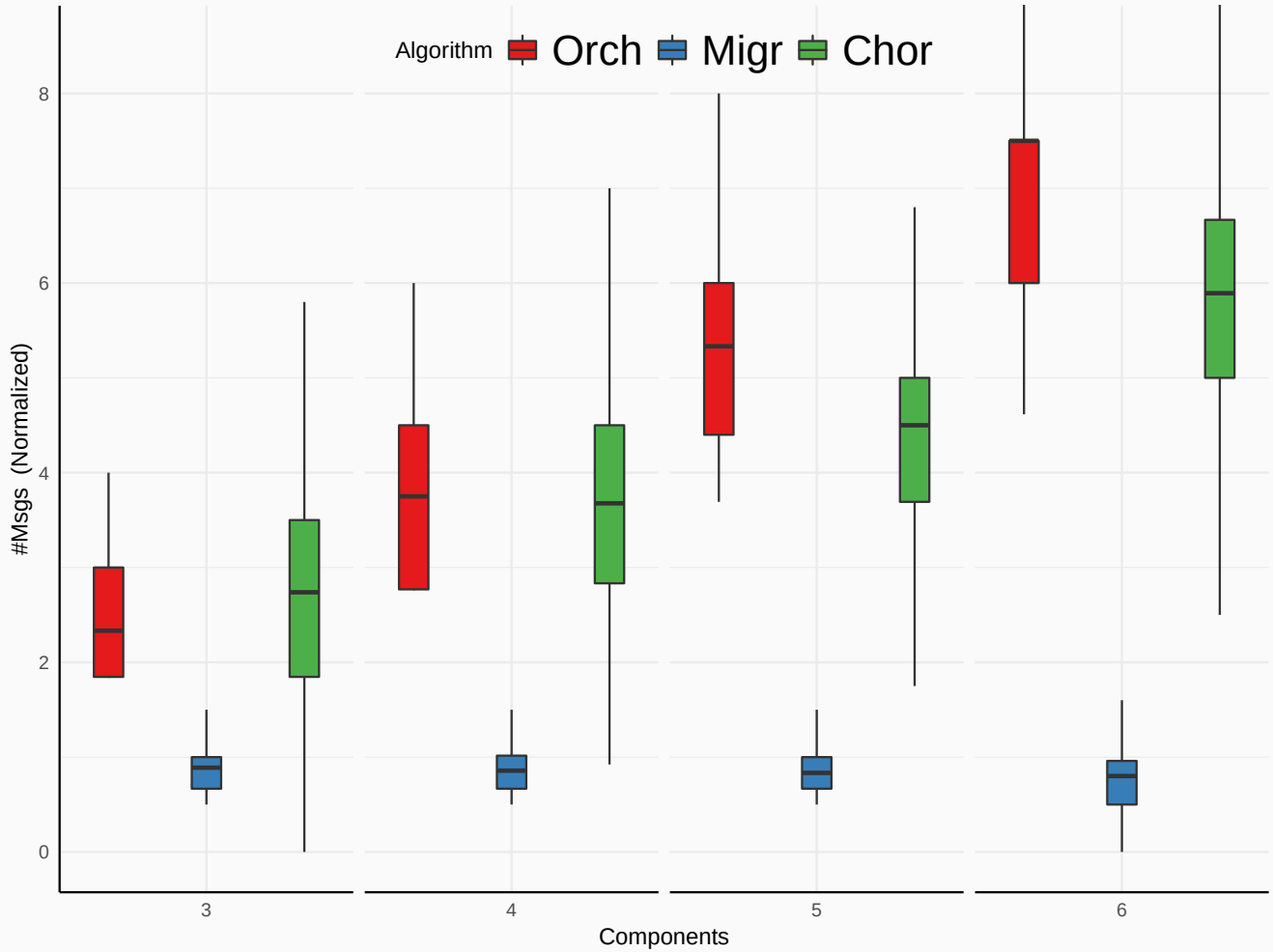
RESULTS ↪ DELAY



Recall from the analysis:

- Orchestration is constant.
- Migration is linear in components.
- Choreography is linear in network depth.

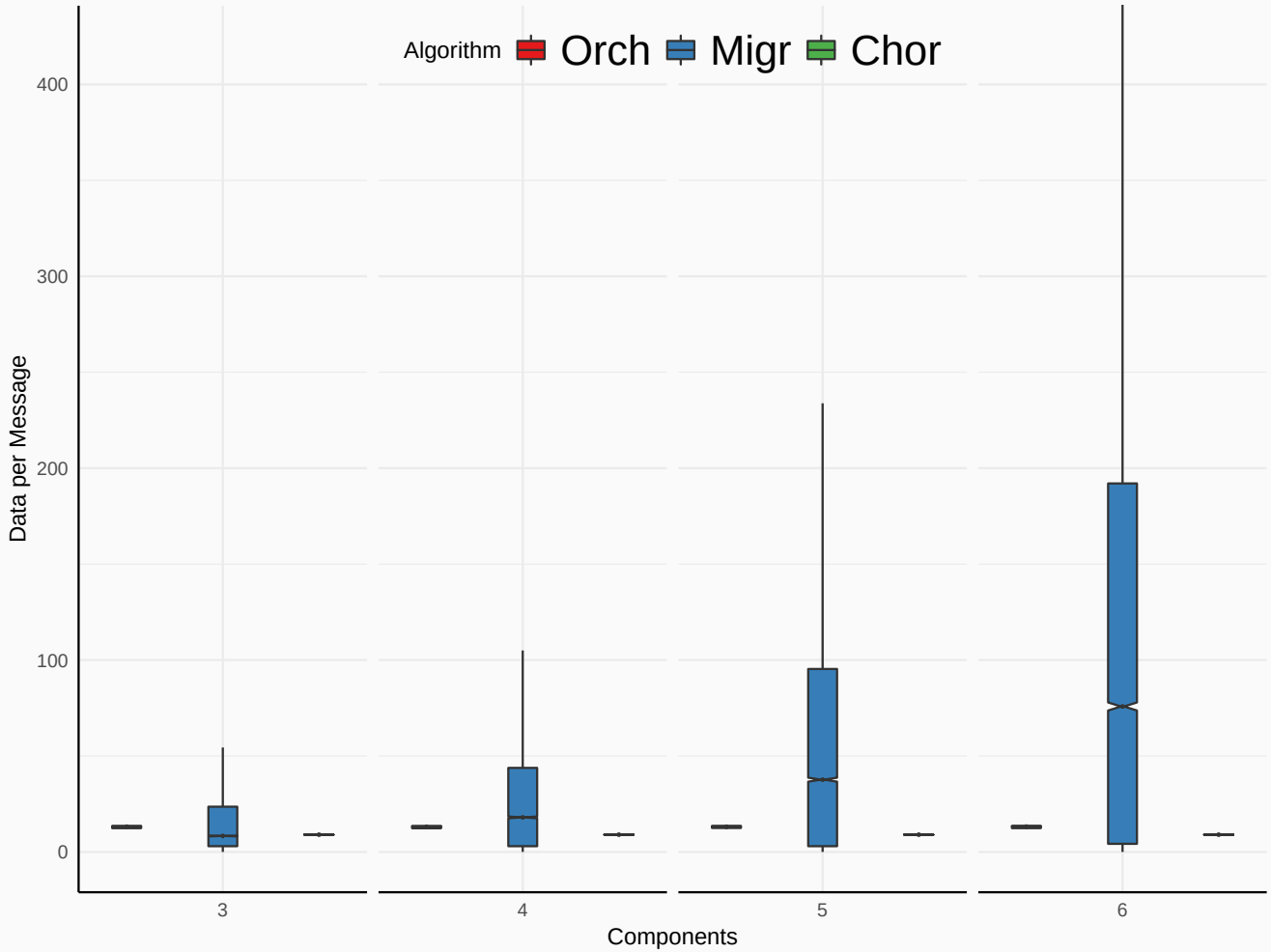
RESULTS ↪ NUMBER OF MESSAGES



Recall from the analysis:

- Orchestration is linear in components.
- Migration is constant.
- Choreography is linear in network edges.

RESULTS ↪ DATA TRANSFERRED



Recall from the analysis:

- Orchestration is constant.
- Migration is exponential in components.
- Choreography is constant.

RESULTS (AVERAGE VALUES)

Alg.	$\lvert\mathcal{C}\rvert$	δ	#Msgs	Data	#S	#S/Mon	Conv
Chor	3	2.37	2.02	18.05	15.27	6.63	0.18
	4	2.49	2.54	22.62	18.22	6.79	0.20
	5	2.37	3.08	27.18	21.29	6.95	0.22
Migr	3	1.02	0.36	49.46	4.80	4.80	1.00
	4	1.38	0.41	128.26	5.67	5.67	1.00
	5	2.28	0.57	646.86	9.40	9.40	1.00
Migrr	3	1.09	0.86	58.02	5.00	5.00	1.00
	4	1.49	0.85	144.62	5.91	5.91	1.00
	5	2.32	0.83	684.81	9.60	9.60	1.00
Orch	3	0.63	1.68	21.01	4.13	4.13	1.00
	4	0.65	2.43	30.42	4.11	4.11	1.00
	5	0.81	3.04	38.51	5.55	5.55	1.00

Lower Conv $\Longrightarrow$ more evenly distributed computation across monitors

Bringing Runtime Verification Home

MONITORED ENVIRONMENT

Amiqual4Home[2]

Experimental platform consisting of a smart apartment, a rapid prototyping platform, and tools for observing human activity.

- Hierarchical setup: 2 floors, 7 rooms, 219 sensors.
- Existing public datasets of full sensors traces (Orange4Home, ContextAct@A4H).
- Databases are annotated with user activities.

Monitoring Context

- 22 specifications written for up to 27 sensors.
- Traces from 07:30 to 17:30 (36,000 timestamps) from Orange4Home.

[2] amiqual4home.inria.fr

PROPERTY GROUPS

- System Properties: ensure system working properly
  - Verify Light Switches (each room i + global house)

$$\text{sc\_light}(i) \stackrel{\text{def}}{=} \square(\text{switch}_i \implies \text{X}(\text{light}_i \,\text{U}\, \neg\text{switch}_i)), i \in [0..n]$$

$$\text{sc\_ok} \stackrel{\text{def}}{=} \bigwedge_{i \in [0..n]} \text{sc\_light}(i)$$

- Activities of Daily Living (ADL): detecting user behavior
  - Formalize an activity as a property over sensors output.
  - A knowledge-based approach (vs. Machine Learning approaches).
  - Examples: sleeping, cooking, watching tv.
- Meta-Properties: properties of other Properties
  - Properties that are defined on top of other properties.
  - firehazard $\stackrel{\text{def}}{=} \square(\text{napping} \implies \neg\text{cooking})$

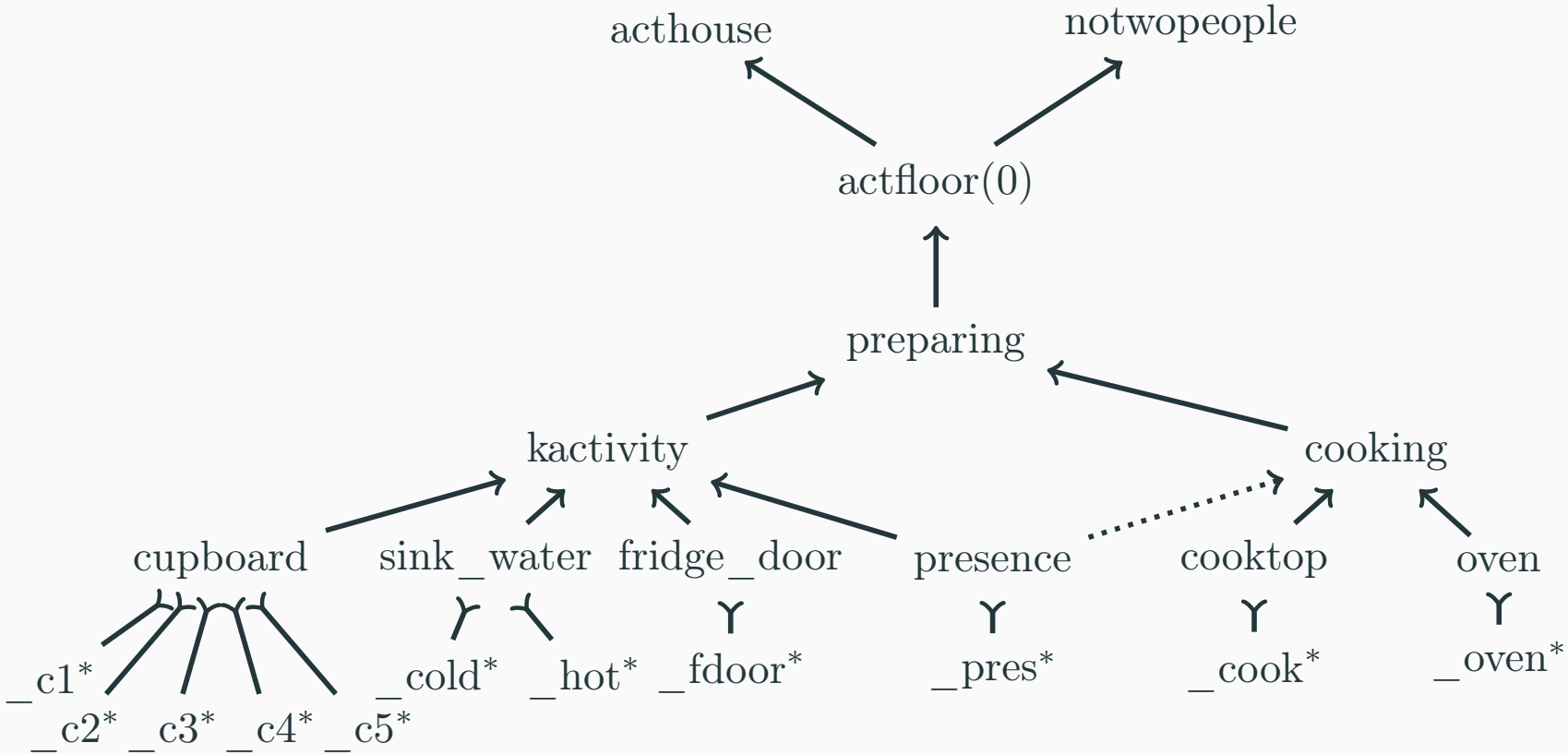
PROPERTIES ↪ EXAMPLE PROPERTIES

ADL	m_toilet	toilet_water
	sink_usage	$\Box_3(\text{m\_bathroom\_sink\_water})$
	bathroom_sink	$\text{bathroom\_sink\_cold} \vee \text{bathroom\_sink\_hot}$
	shower_usage	$\Box_2(\text{m\_bathroom\_shower\_water})$
	napping	$\Box_{25}(\text{m\_bedroom\_bed\_pressure})$
	dressing	$\Diamond_4(\text{m\_bedroom\_closet\_door} \vee \text{m\_bedroom\_drawers}))$
	reading	$\text{m\_bedroom\_light} \wedge \Diamond_4(\neg\text{dressing} \wedge \neg\text{napping})$
	office_tv	$\Diamond_3(\text{m\_office\_tv})$
	computing	$\Diamond_3(\text{m\_office\_deskplug})$
	livingroom_tv	$\Diamond_3(\text{m\_livingroom\_tv} \wedge \text{m\_livingroom\_couch})$
	eating	$\neg\text{m\_kitchen\_presence} \wedge \Box_6(\text{m\_livingroom\_table})$
Meta	actfloor(0)	$\text{cooking} \vee \text{preparing} \vee \text{eating} \vee \text{washing\_dishes} \vee \text{livingroom\_tv} \vee \text{m\_toilet}$
	acthouse	$\text{actfloor}(0) \vee \text{actfloor}(1)$
	notwopeople	$\neg(\text{actfloor}(0) \wedge \text{actfloor}(1))$
	firehazard	$\text{napping} \implies \neg\text{cooking}$

DECENTRALIZATION ↪ TAKING ADVANTAGE OF HIERARCHIES

1. Abstraction/Modularity
   - 1.1 Sub-specifications are building blocks for more complex specifications.
   - ⋆ (Meta) Specifications of specifications.
   - 1.2 Change (or refine) existing sub-specifications without changing those that depend on them.
   - 1.3 Abstraction from Implementation: references should eventually return a verdict.
2. Scalability/Efficiency
   - 2.1 Factor the monitoring cost of sub-specifications.
   - 2.2 Smaller automata/formulae to represent complex inter-dependent specifications (Monitor Synthesis).
   - 2.3 Manage duplication of computation and computation.
   - 2.4 Communication modeled by dependencies.
   - 2.5 Monitor placement can be optimized for system architecture.

Decentralized Specifications ↪ Dependency Hierarchies & Reference



+ Reduction of atomic propositions and size of specifications
+ Re-use: no need to recompute same dependencies
+ Abstraction: references hides implementation

MONITOR SYNTHESIS ↪ ATOMIC PROPOSITIONS

- Synthesizing monitors is doubly exponential.
  1. Number of atomic propositions
  2. Size of formula

★ Goal: Reference Sub-specifications
- Reduce number of atomic propositions ($|\mathrm{AP}|^{\mathrm{d}} < |\mathrm{AP}|^{\mathrm{c}}$)
- Reduce formula size (atomic proposition instead of formula)

Name	$\lvert\mathrm{AP}\rvert^{\mathrm{d}}$	$\lvert\mathrm{AP}\rvert^{\mathrm{c}}$	d
sc_light(i)	2	2	1
sc_ok	4	8	2
toilet*	1	1	0
sink_usage	1	2	1
napping	1	1	1
dressing	2	3	1
reading	3	5	2
kactivity*	4	9	1
preparing	2	11	2
actfloor(0)	6	16	3
actfloor(1)	7	11	3
acthouse	2	27	4
notwopeople	2	27	4
firehazard	2	3	2

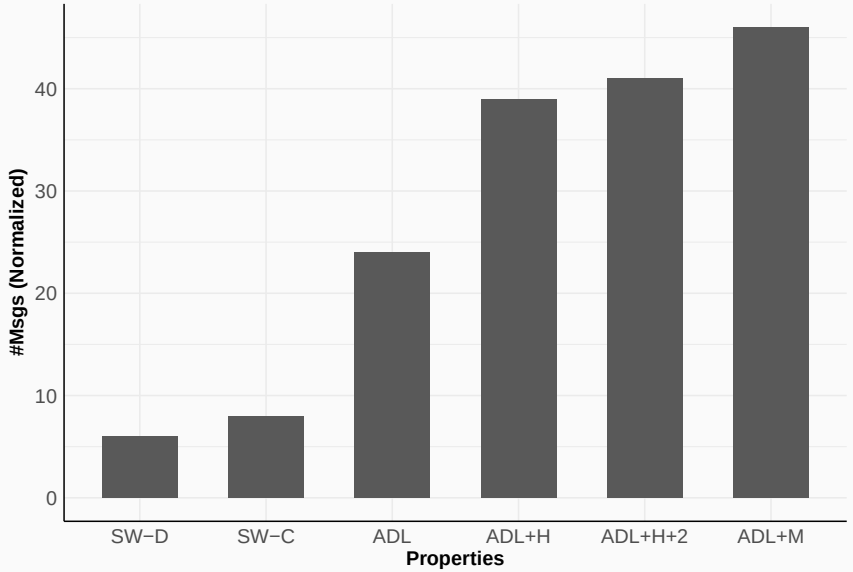
RE-USING COMPUTATION AND COMMUNICATION

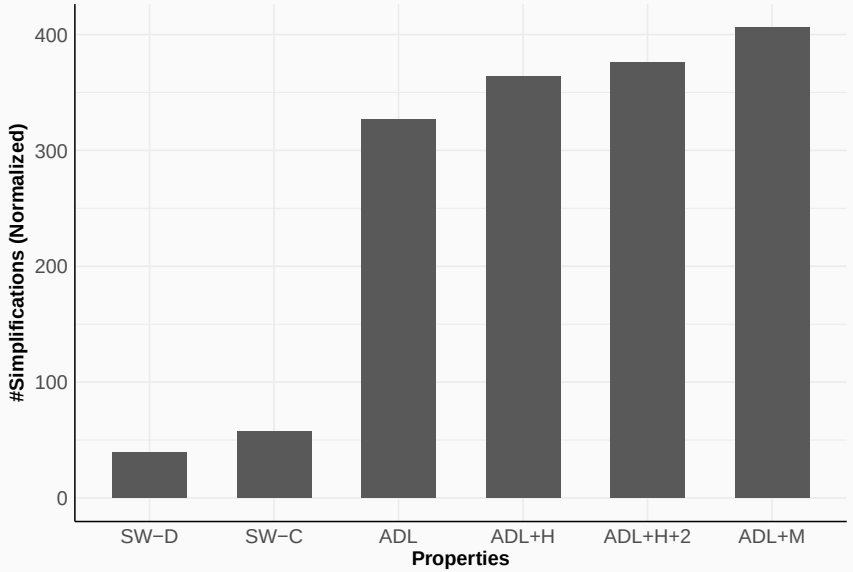
- A shared sub-specification is monitored once.
- Higher-up specifications do not need the sub-specification sensors.
  - Centralized sc_ok (SW-C) uses 8 sensors instead of 6 for decentralized (SW-D).
- Adding meta-properties incurs less overhead due to re-use.

ADL	All ADL properties (baseline)
ADL+H	ADL + actfloor(i) ($i \in [0..1]$), acthouse
ADL+H+2	ADL+H + notwopeople
ADL+M	All meta properties

$$\text{acthouse} \stackrel{\text{def}}{=} \text{actfloor}(0) \vee \text{actfloor}(1)$$

$$\text{notwopeople} \stackrel{\text{def}}{=} \neg(\text{actfloor}(0) \wedge \text{actfloor}(1))$$

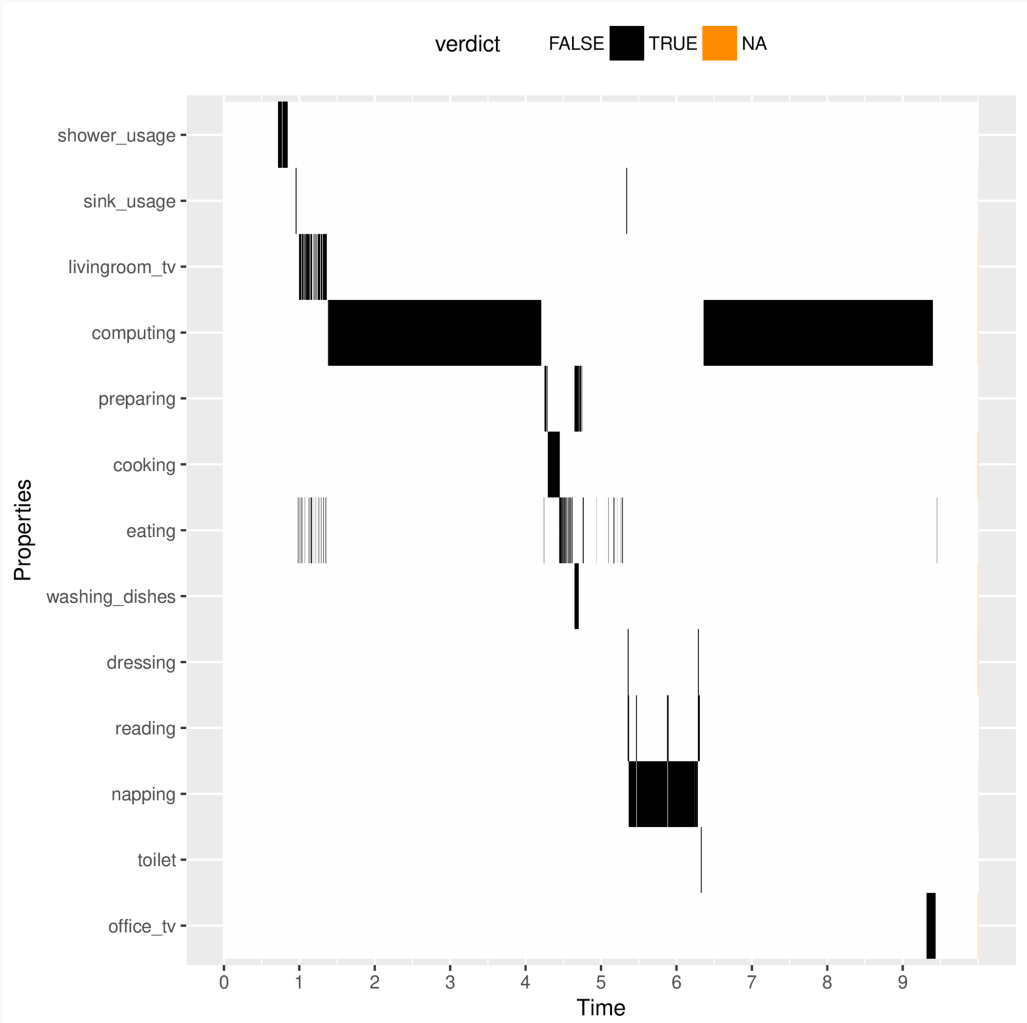




SCHEDULE

Suggested (left) vs Reconstructed (right)

08:00	Entering	Entrance	12:00	Eating	Livingroom
	Up	Staircase		Dishes	Kitchen
	Shower-ing	Bathroom		Cleaning	Kitchen
			13:00	Up	Staircase
	Sink	Bathroom		Sink	Bathroom
08:30	Down	Staircase	13:15	Dressing	Bedroom
	TV	Livingroom		Reading	Bedroom
09:00	Up	Staircase	13:45	Napping	Bedroom
	Comput-ing	Office		Dressing	Bedroom
			14:00	Comput-ing	Office
			16:30	TV	Office
11:30	Down	Staircase		Down	Staircase
	Prepar-ing	Kitchen	17:00	Leaving	Entrance
	Cooking	Kitchen			



HOW GOOD IS OUR METHOD AT DETECTING ADL?

★ Depends on Property
- Availability of sensors
- Rigidity of specification

- Examples:

toilet: only water usage $\Longrightarrow$ low recall
reading: no sensors $\Longrightarrow$ inferred from others
napping: changing specification

Formula	Precision	Recall	F1
$\Box_{25}(\text{weight})$	0.43	0.95	0.60
$\Box_{3}(\text{weight})$	0.43	0.99	0.60
$\Diamond_{3}(\text{weight})$	0.43	1.0	0.60
$\Box_{3}(\text{pres} \wedge \text{weight})$	0.34	0.14	0.20
$\Box_{3}(\neg\ell \wedge \text{weight})$	1.00	0.97	0.99

weight: bed pressure sensor
pres: bedroom presence sensor
ℓ: bedroom light sensor

Property	Precision	Recall	F1
computing	0.98	0.99	0.99
office_tv	1.00	0.80	0.89
cooking	0.88	0.88	0.88
shower_usage	1.00	0.50	0.67
washing_dishes	1.00	0.47	0.64
livingroom_tv	1.00	0.43	0.60
dressing	1.00	0.41	0.58
toilet*	1.00	0.18	0.30
sink_usage	1.00	0.13	0.23
eating	0.61	0.35	0.44
napping	0.43	0.95	0.60
preparing	0.23	0.77	0.35
reading	0.37	0.04	0.06

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.
5. Application to smart homes.

★ Future Work

1. Centralised specification → equivalent decentralized specifications.
   - Optimize existing methods.
   - Take into account topology of the monitored system.
2. Extend THEMIS (metrics, better visualization of algorithm behavior).
3. Runtime enforcement of centralized and decentralized specifications.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Related Work and Goals

RELATED WORK ↪ DECENTRALIZED RV

- General setting
  - $\mathcal{C}$: a set of components
  - AP: a set of atomic propositions, partitioned by $\mathcal{C}$
- Issues in decentralized monitoring
  - partial views of AP – unknown global state
  - partial execution of the automaton (evaluation)
  - communication between monitors
- Rewriting-based techniques
  - (safety) LTL [Rosu et al 05], (full) LTL [BauerFalcone12,ColomboFalcone16]
  - (safety) MTTL (real-time systems) [ThatiRosu05,Basin et al 15]
  - Common assumptions
    - Reliable network with fully-connected components
    - Global clock
    - Oblivious to order of messages

(!) Unpredictable runtime behavior of rewriting

→ Hard to compare various strategies

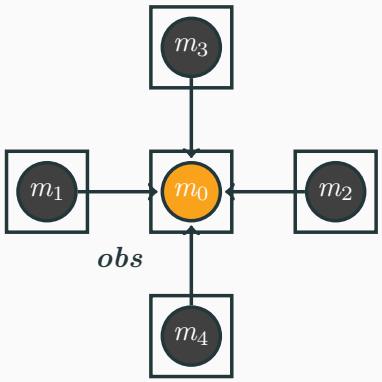
RELATED WORK ↪ DECENTRALIZED RV (CONT'D)

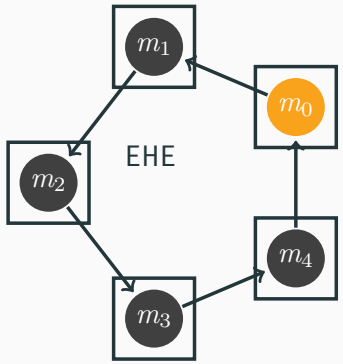
- Automata-based techniques for regular languages [Falcone et al 14]
  - Same assumptions as rewriting
  + More expressive than LTL
  + Predictable behavior
  – Tightly linked to specification (synthesis)
  – No monitor topology nor communication strategy
- Monitor Consensus [MostafaBonakdarpour16]
  - monitors deciding the same verdict
  - Assumptions
    - Fully-connected components
    - Asynchronous Systems (Alternating Numbers)
    + Unreliable links (Monitors + System)
    – $2k + 2$ verdicts when resilience up to k failures

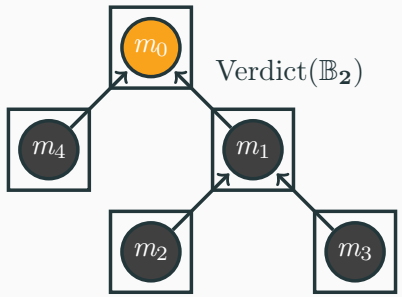
  → Determine consensus on a verdict in case of failures

(!) All monitors check the same specification

STUDYING EXISTING ALGORITHMS







- Example algorithms
  - Orchestration: Central monitor + forwarding monitors.
  - Migration: Specification hops from one component to another.
  - Choreography: Monitors are organized in a tree.
- Expected behavior of algorithms:

Algorithm	δ	# Msg	|Msg|
Orchestration	$\Theta(1)$	$\Theta(\|\mathcal{C}\|)$	$\Theta(\|AP_c\|)$
Migration	$\mathcal{O}(\|\mathcal{C}\|)$	$\mathcal{O}(m)$	$\mathcal{O}(\|Q\|^{\|\mathcal{C}\|})$
Choreography	$\mathcal{O}(\text{depth}(\text{rt}) + \|\text{tr}\|)$	$\Theta(\|E\|)$	$\Theta(1)$