Verifying Opacity of Discrete Timed Automata

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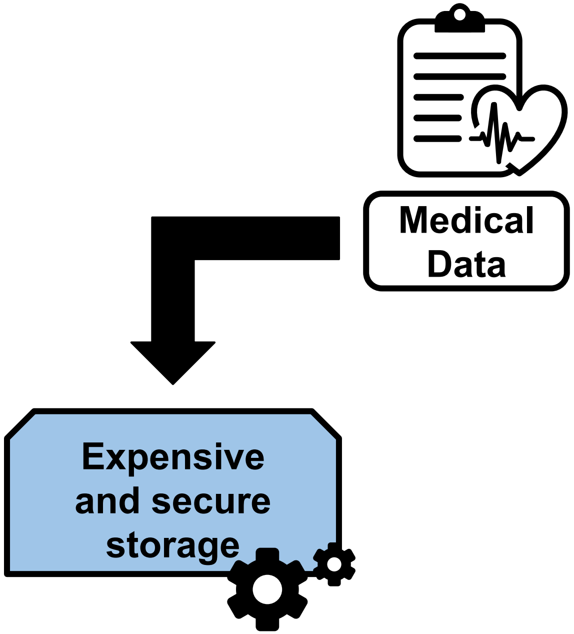
SOFTWARE AND EMBEDDED SYSTEMS ENGINEERING

Motivation

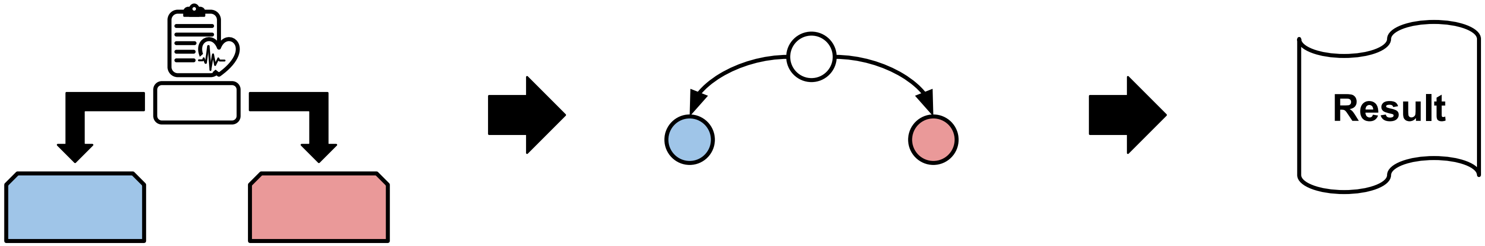

Medical Data
Expensive and secure storage
Cheap and vulnerable storage

Motivation

- Opacity to guarantee confidentiality
- Formal verification requires accurate model (TA)

Problem: Opacity verification of TA is **undecidable**

➔ **Restriction required**



Real System | **Formal (Timed) Model** | **Verification**

Goal

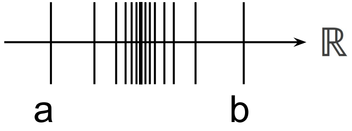
Goal: Verify opacity of TA with **minimal** restrictions

Criteria:

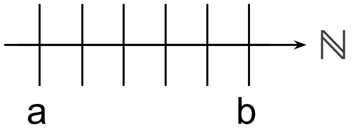
- **Safe**: no restrictions on the notion of opacity
- **Applicable**: no restrictions on the class of TA
- **Scalable**: large TA can be verified in reasonable time

Key Idea: Discrete-time setting to make opacity verification problem decidable.

Dense Time

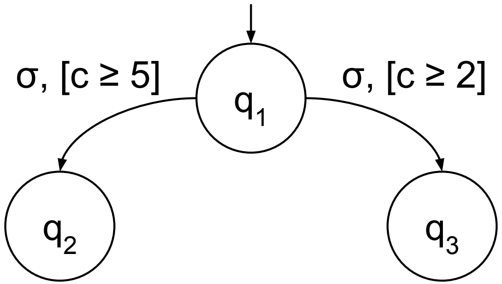


Discrete Time



Background: Opacity

S:



Assumption:
Attacker knows structure of **S**

Background: Opacity

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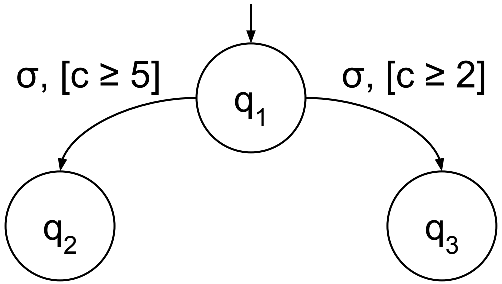

Assumption:
Attacker knows structure of **S**

- Multiple notions of opacity in the literature

➔ Equivalent in our setting

Background: Opacity

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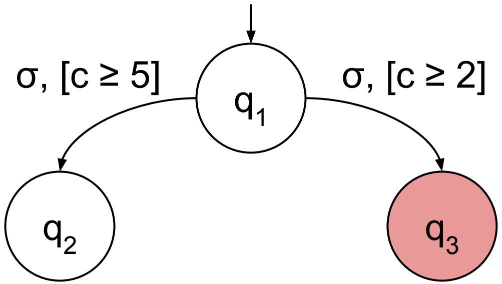

Assumption:
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- Multiple notions of opacity in the literature

➔ Equivalent in our setting

Example: Current-State Opacity (CSO)

Question: Is the current state a secret state?

$(\sigma, 7) \rightarrow q_2$ and q_3 can be active

$(\sigma, 2) \rightarrow$ only q_3 can be active!

Related Work

- Literature considers only **dense time** setting
- Two restrictions to overcome undecidability:
  - Weaken notion of opacity
  - Restrict class of TA

Authors	Approach	Applicable	Safe
André et al, 2023 **[3]**	Measure only total runtime	✔	✘
Ammar et al, 2021 **[4]**	Time is bounded	✔	✘
Zhang, 2024 **[5]**	Real Time Automata	✘	✔
Wang and Zhan, 2018 **[6]**	Real Time Automata	✘	✔
Marques et al, 2023 **[7]**	Real Time Automata	✘	✔
Li et al, 2021 **[8]**	Weighted Automata (weight = time instance)	✘	✔

Our Method

Two-Step Verification Method

TA

↓

Step 1: Transformation

Transform timed automaton (TA) to equivalent finite tick automaton (τ-FA)

↓

τ-FA

↓

Step 2: Verification

Employ known opacity verification approach for FA

↓

Result

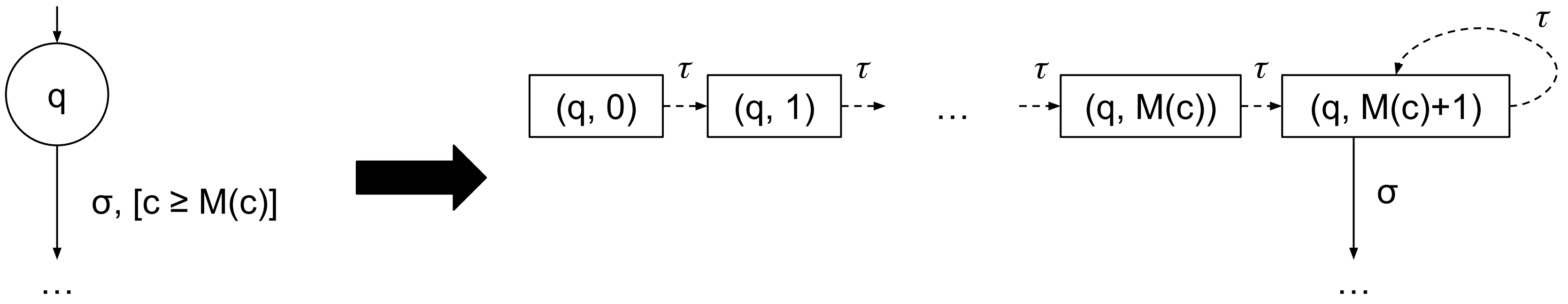
Transformation

- Transformation from single clock TA to τ-FA, Gruber et al. (2005) [1]
- Extension to TA with **arbitrary many** clocks

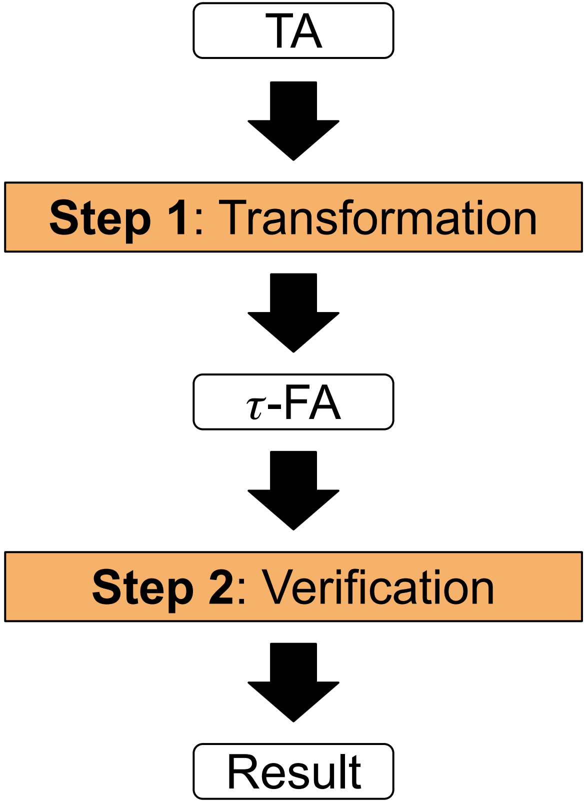
Idea: use standard region abstraction $\boldsymbol{\alpha_R}$:

- M(**c**) = largest constant that can be compared to clock **c**

➔ all k > M(**c**) cannot be distinguished



State Explosion



Problem:
Opacity verification scales **exponential**
➔ Small τ-FA required!

- $\boldsymbol{\alpha}_R$ produces more states than necessary

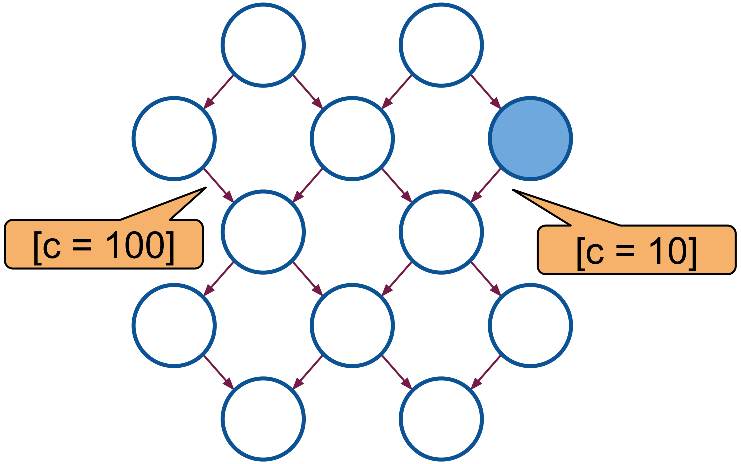
➔ Tighter time abstraction to improve scalability

Local Time Abstraction

Standard region abstraction α_R:

For a clock **c**

- Collect **all** locations in set **Q**
- Largest constant determines number of states



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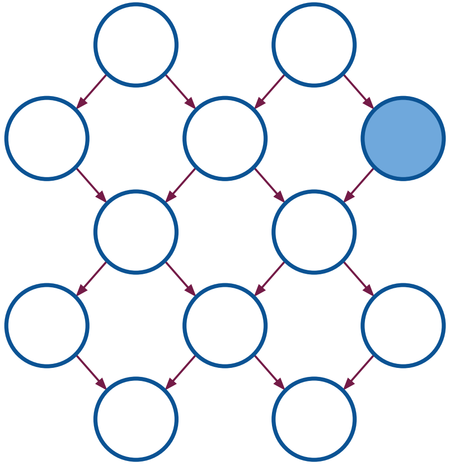
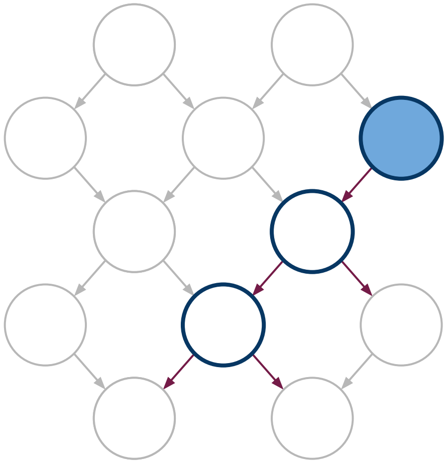


Local time abstraction α_L:
For a clock **c**
- Collect **specific** locations in set **Q'**

➔ Largest constant determines number of states



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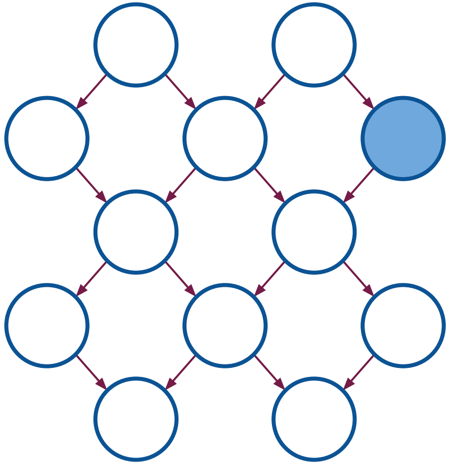

Collect **only** locations that can distinguish clock values of **c** (**Clock Reach**)

Local time abstraction α_L:
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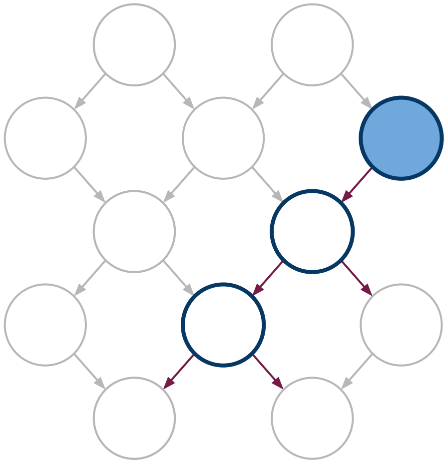

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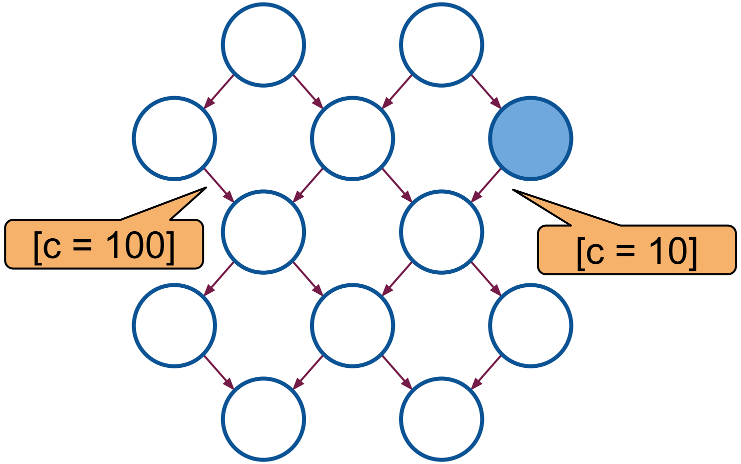

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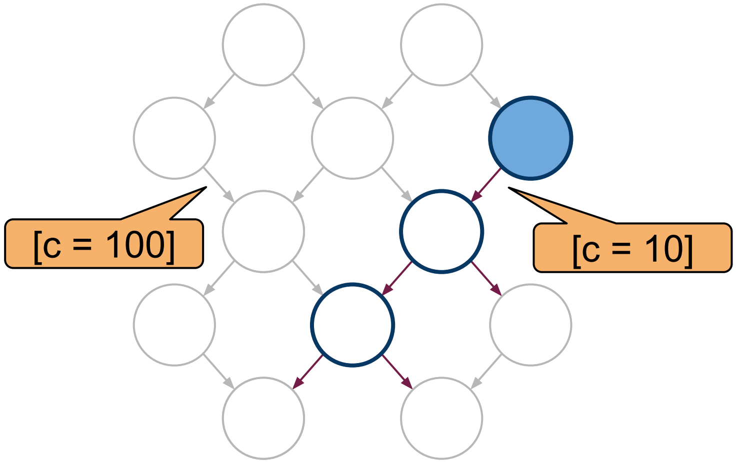


Evaluation

Observation: Computation of α_L is more expensive than computation of α_R

Question 1: How significant is the **cost** of computing α_L?
Question 2: How significant are the **overall gains** due to the **state reduction** of α_L?

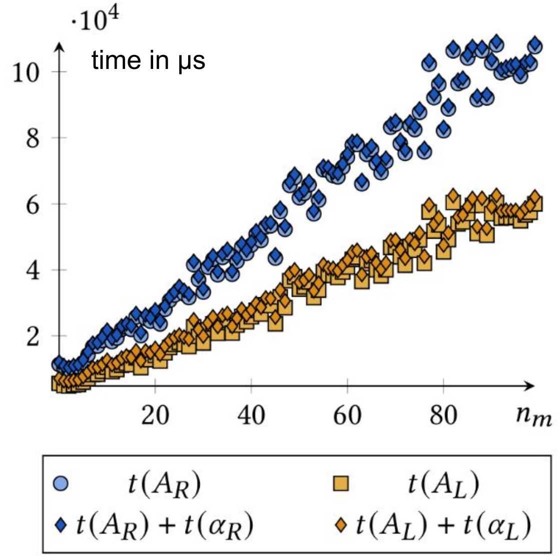
Randomized Systems

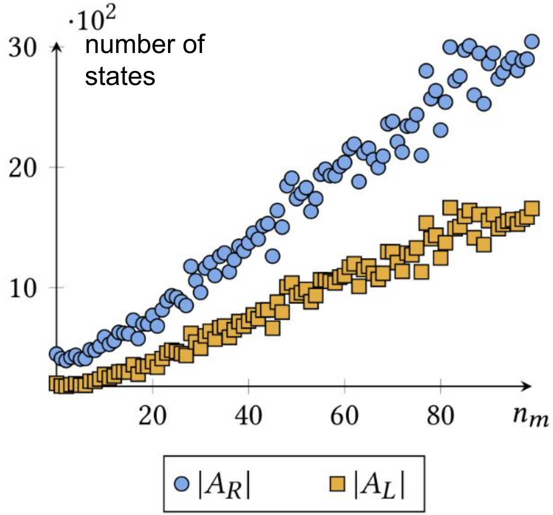
- Scaled by parameter
- No assumptions on system structure
- Average over all possible systems

Case Studies

- Realistic systems found in literature
- Logical structure
- Allow comparison in future works

Randomized Systems





Abbreviations:

- **n_m** = largest constant in any guard of TA
- **α** = time abstraction
- **A** = tick automaton

Standard region abstraction α_R

Local time abstraction α_L

Case Studies

Four realistic case studies:

- ➔ A_C : **Cloud service** to purchase products online **[3]**
- ➔ A_M : **Medical cloud** service to process patient data **[8]**
- ➔ A_S : **Sensor network** to locate agent in area **[9]**
- ➔ A_A : **ATM** with password authentication **[10]**

Case Study	Properties of case studies				Computation time of abstraction in µs		Number of states of the τ-FA		Time to verify Opacity in µs		Saved
	|L|	|Δ|	M	opaque	α_R	α_L	α_R	α_L	α_R	α_L	
A_C	18	20	21	yes	0.34	3.43	1301	175	216.38	29.82	**-86.22%**
A_M	8	10	10	no	0.29	0.55	96	49	22.06	9.83	**-55.42%**
A_S	25	64	20	yes	0.85	1.71	800	299	443.53	112.63	**-74.61%**
A_A	16	23	100	no	0.91	17.48	22909	12121	98782.03	37693.67	**-61.84**

Conclusion

Contributions:

- Novel algorithmic approach to verify opacity of timed automata

➔ Opacity verification is decidable in discrete time

- Local time abstraction to improve scalability of verification method by 55%-86%

Future Work:

- Explore more compact time models that avoid time step enumeration
- Investigate opacity enforcement techniques for our model

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