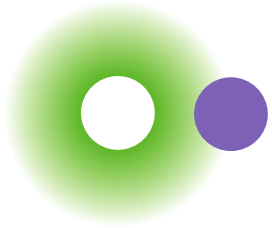
From propositional to first-order monitoring

Jan-Christoph Küster

Joint work with Andreas Bauer and Gil Vegliach



NICTA

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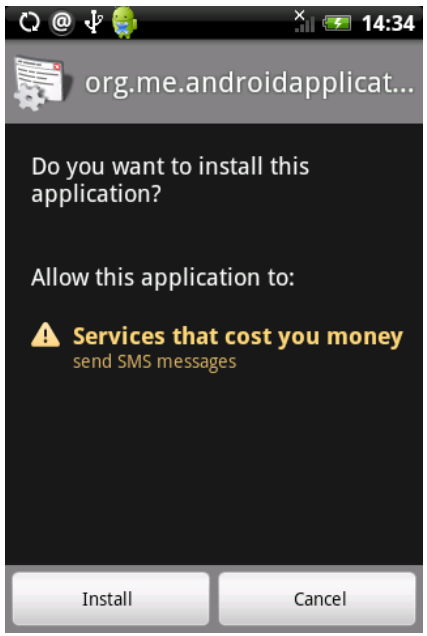
Why first-order monitoring?

Checking security properites of **systems with data**, e.g., smartphones.



- Trojan-SMS.AndroidOS.FakePlayer.A
- While displaying *“Wait, sought access to video library. . . ”*, app sends string *“798657”* in SMS to Russian premium numbers.

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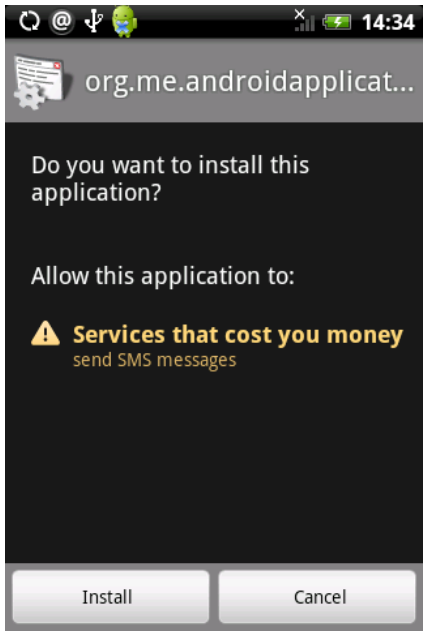

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Security property (syntax)

*"Don't send an SMS to **anyone** not in my contact book"*:

$$\mathbf{G} \forall x : sms.\ contact(x)$$

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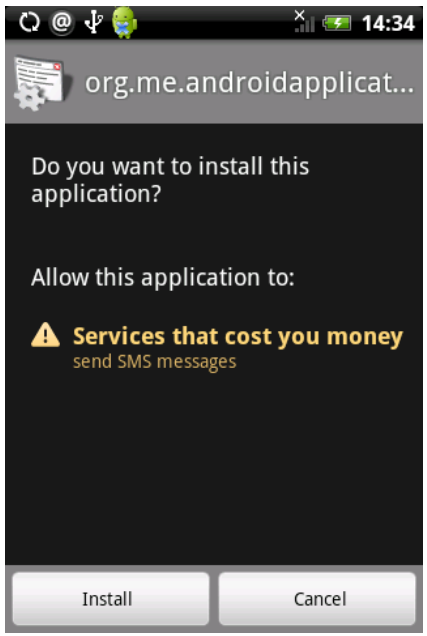

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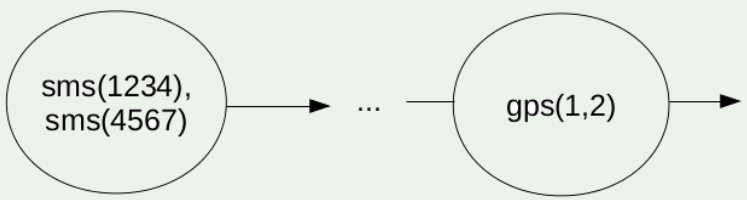
Trace (semantics)



Spawning automaton

$$\mathcal{L}(\mathcal{A}_\varphi) = \mathcal{L}(\varphi)$$

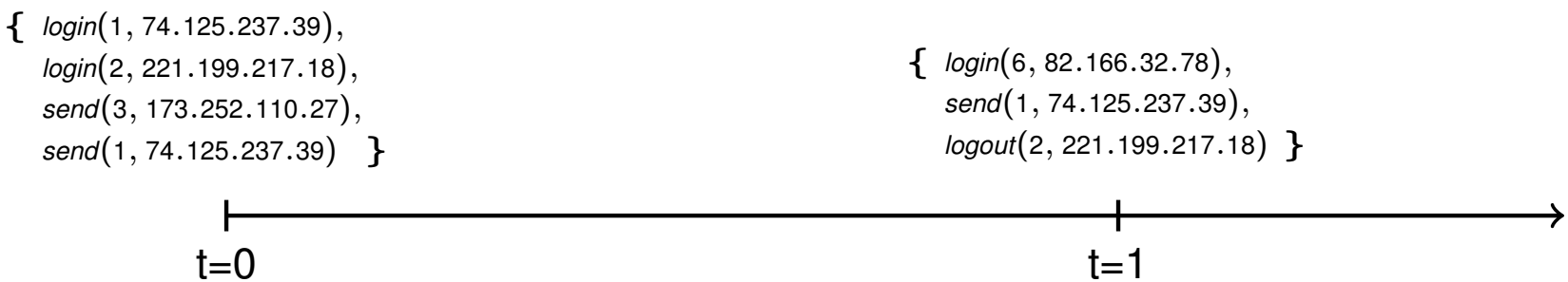
for $\varphi \in \mathrm{LTL}^{\mathrm{FO}}$

Spawning automaton

Example

Once **user** *u* has **logged in** to the system from **IP-address** *ip*, she must **not send** anything from an IP-address **other than ip** until **logged out**.

$$\mathbf{G}\ \forall(u, ip) : login.\ \forall(u', ip') : send.\ \big(eq(u, u') \Rightarrow eq(ip, ip')\big)\ \mathbf{U}\ logout(u, ip)$$



Spawning automaton

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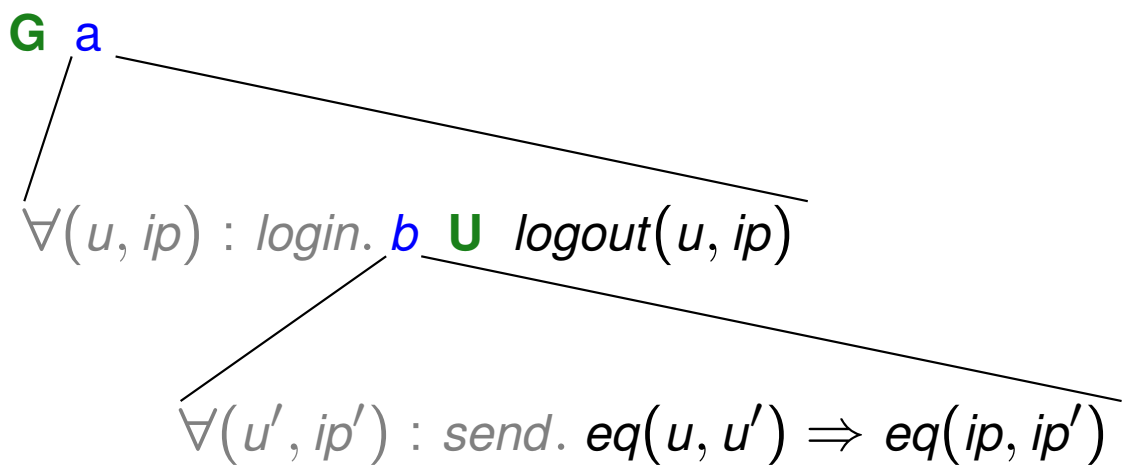
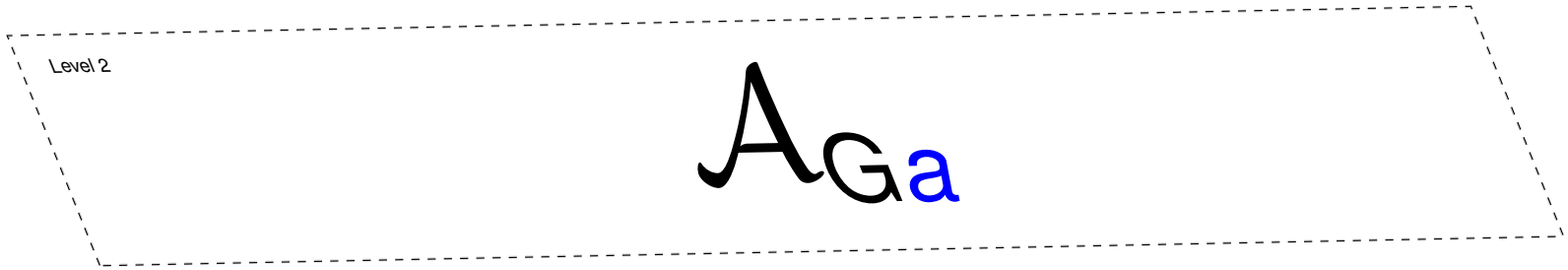


Spawning automaton

Example



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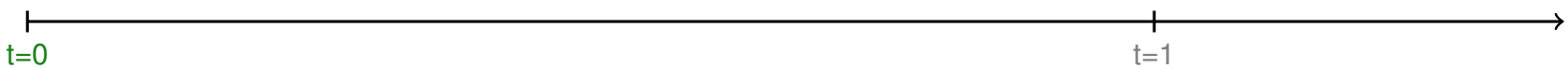

Spawning automaton

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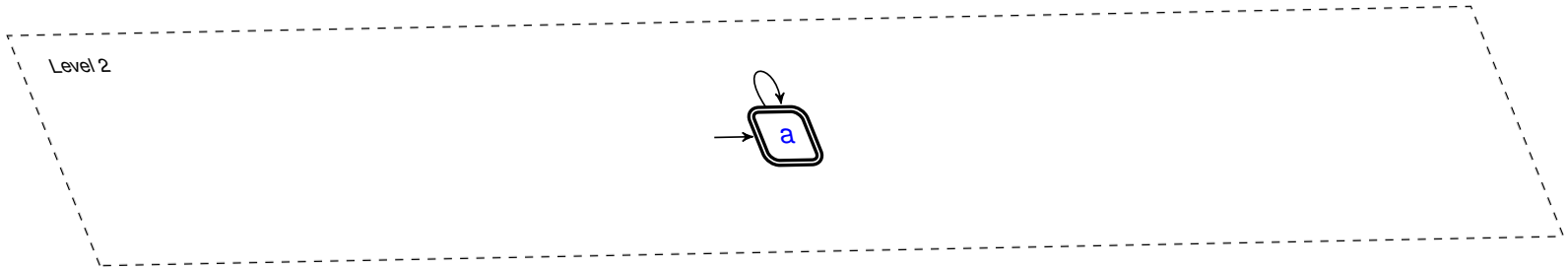

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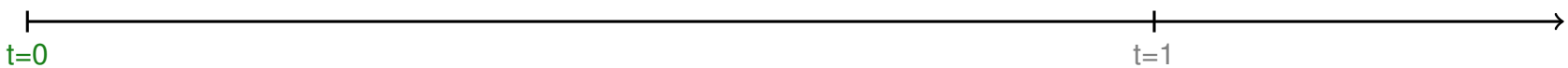

Spawning automaton

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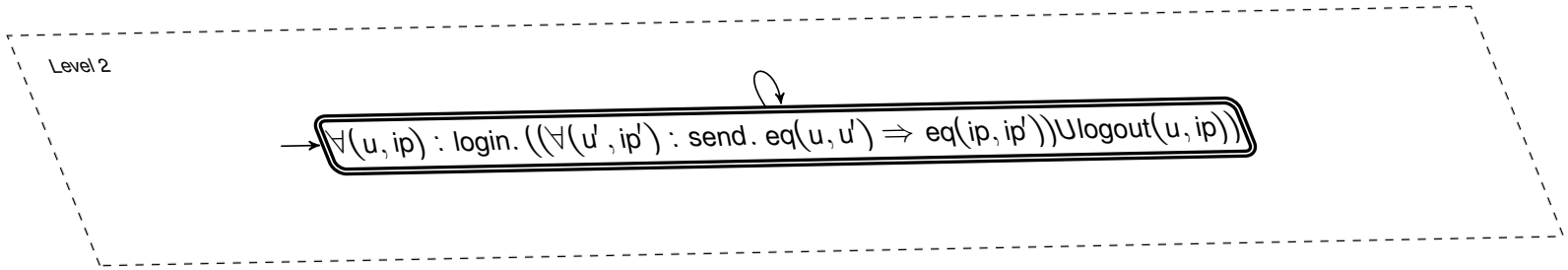

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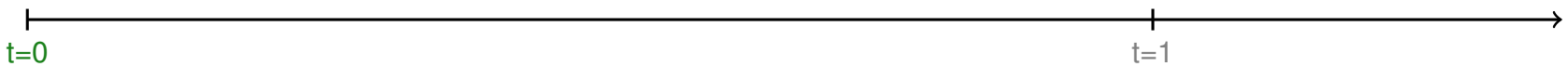

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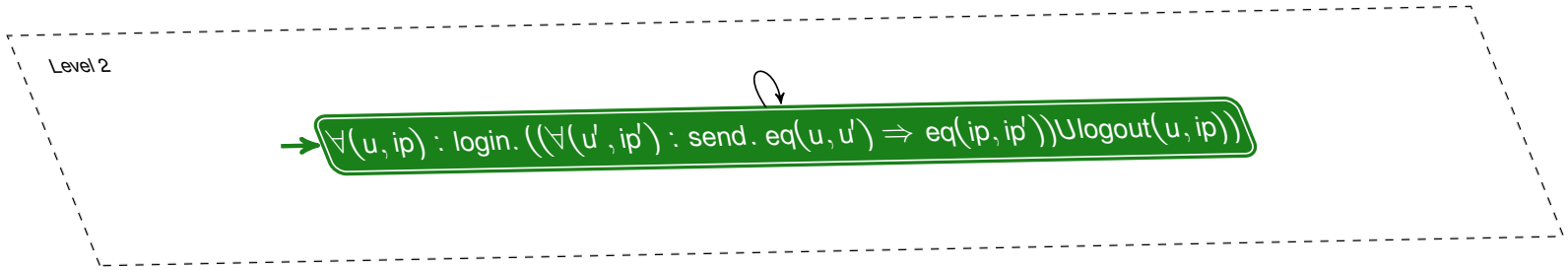

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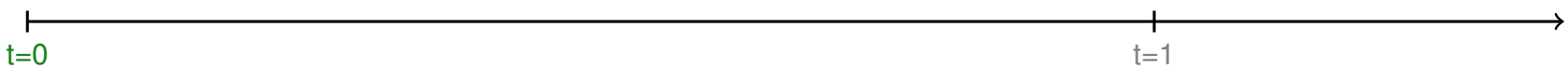

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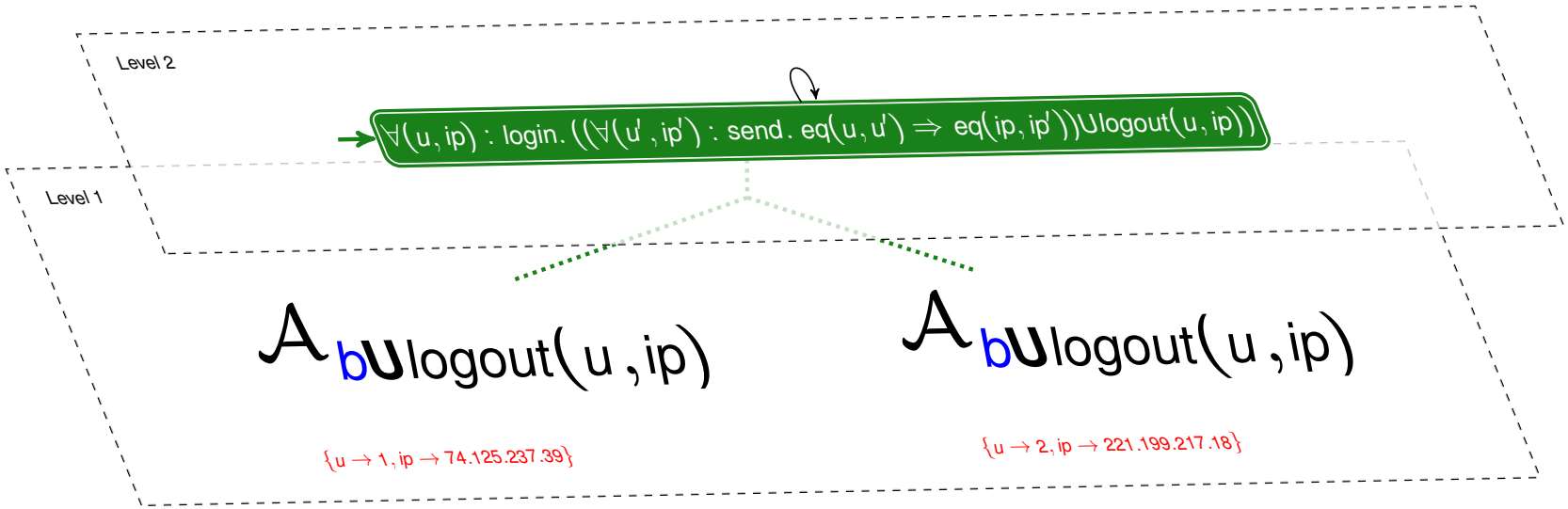

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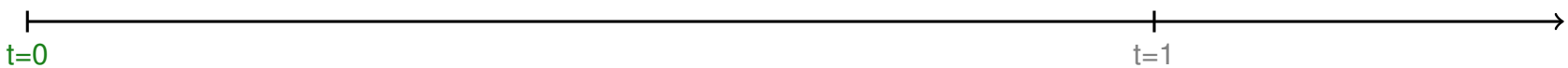

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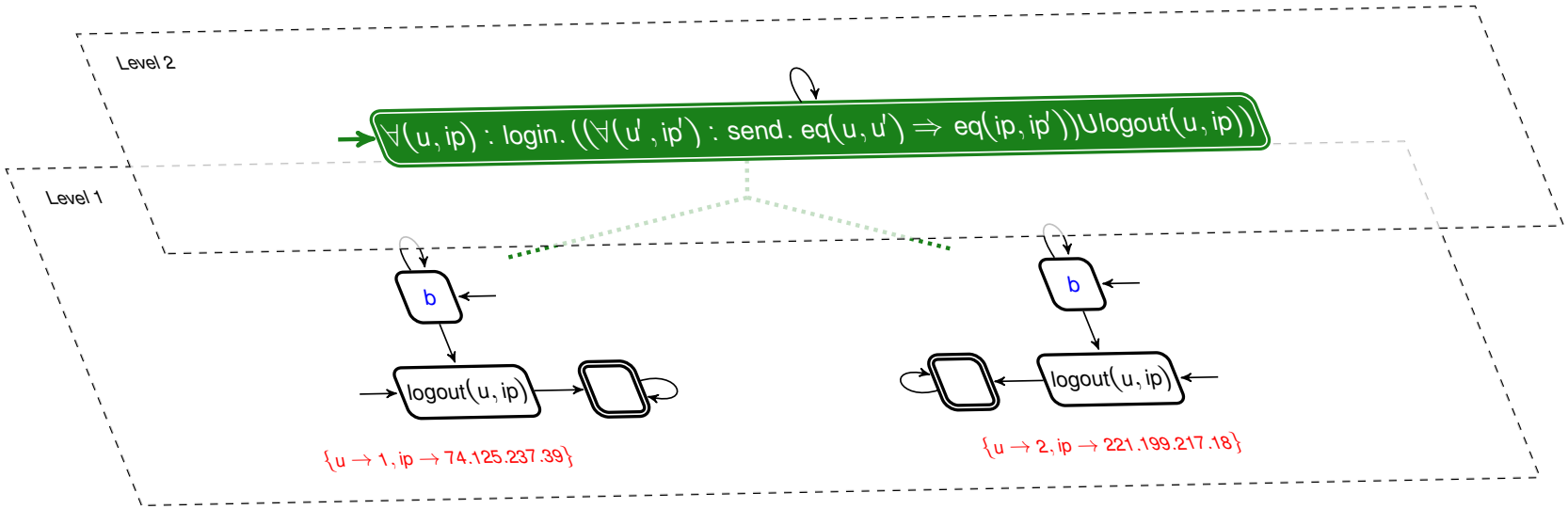

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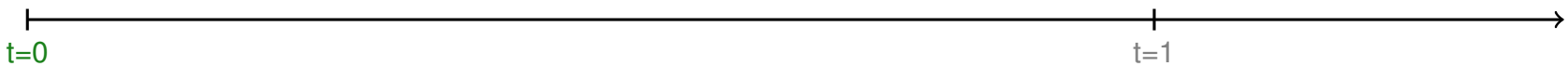

Spawning automaton

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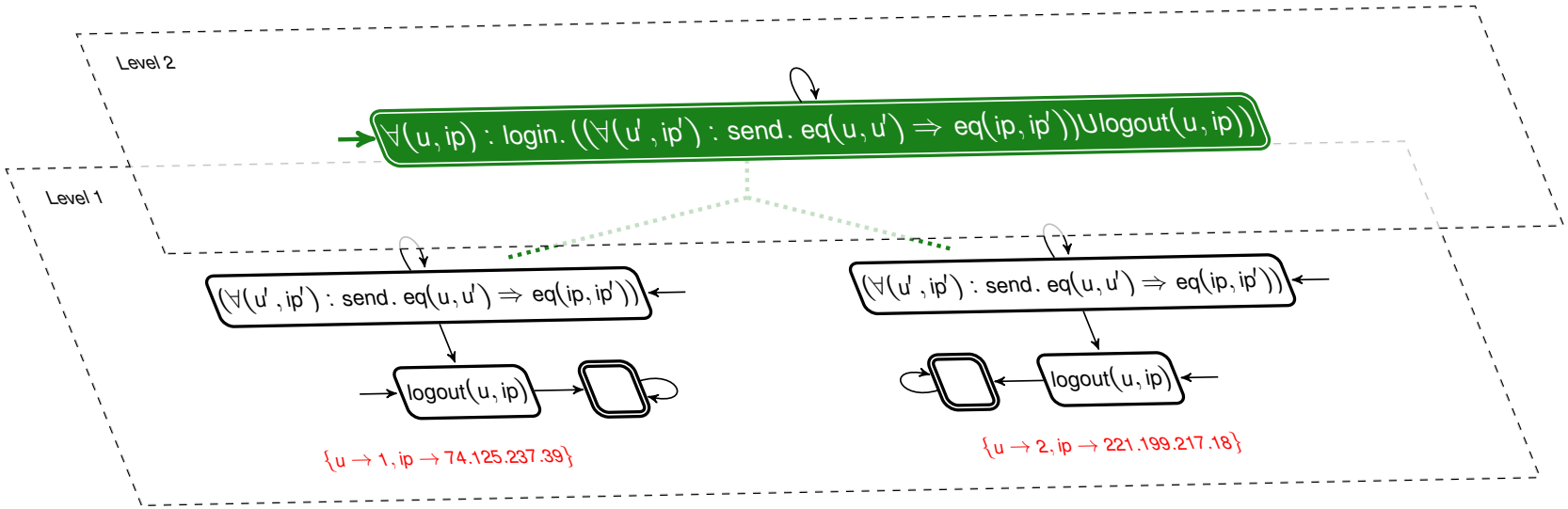

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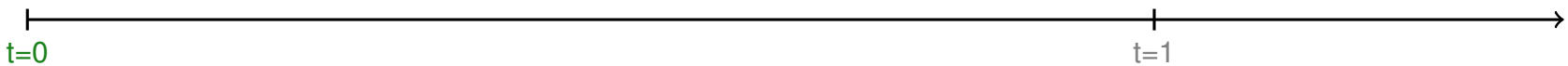

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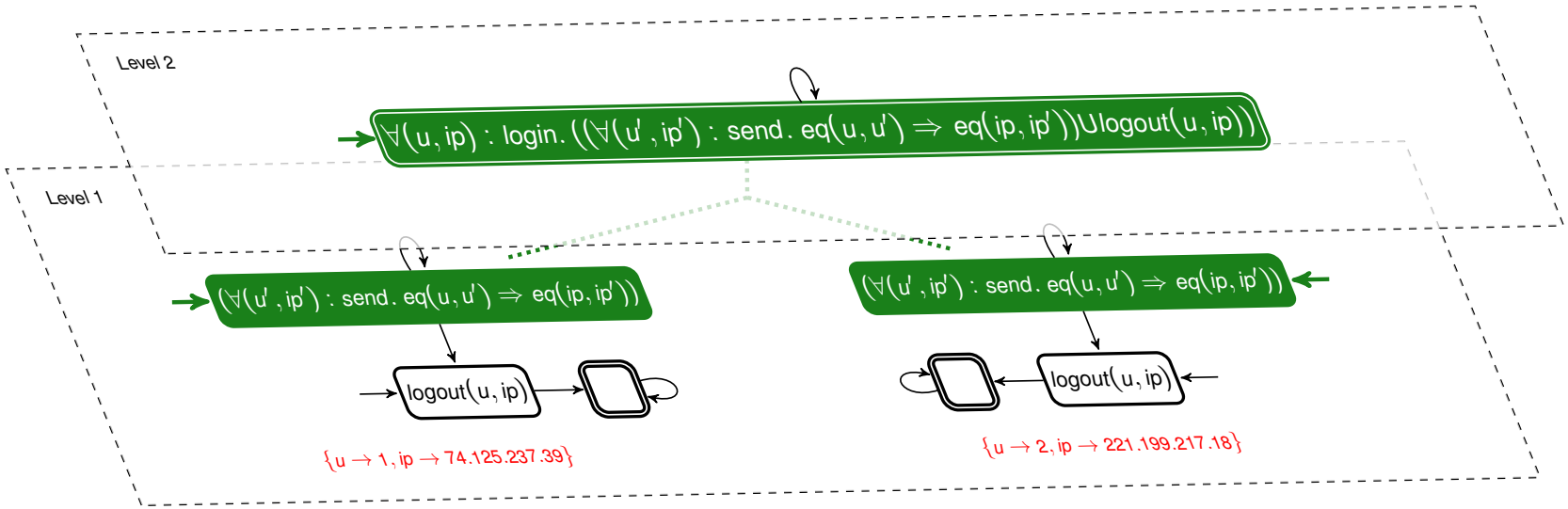

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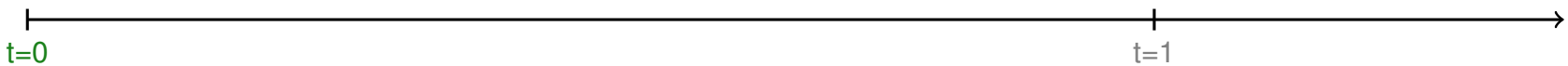

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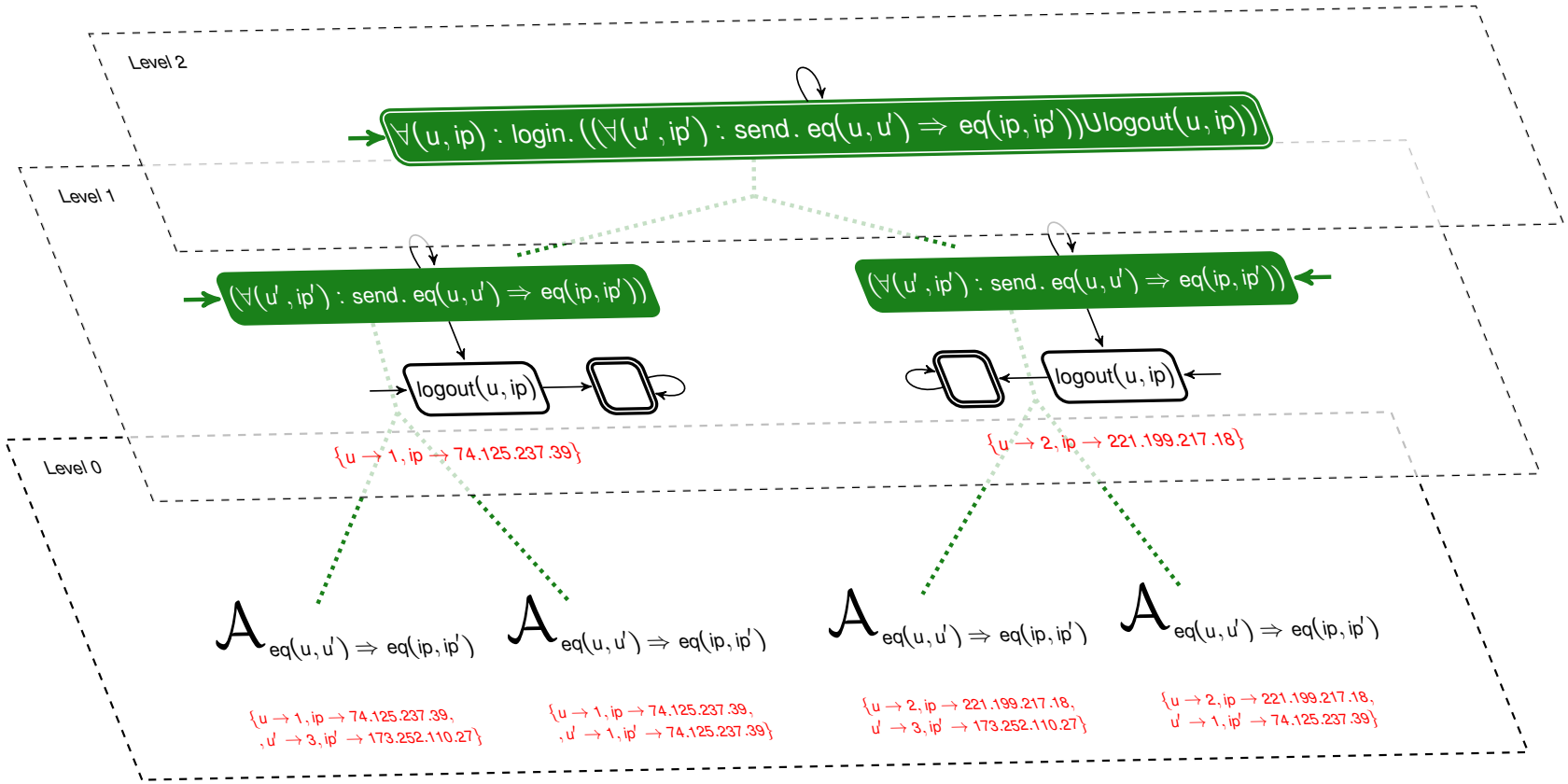

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t=0 t=1

Spawning automaton

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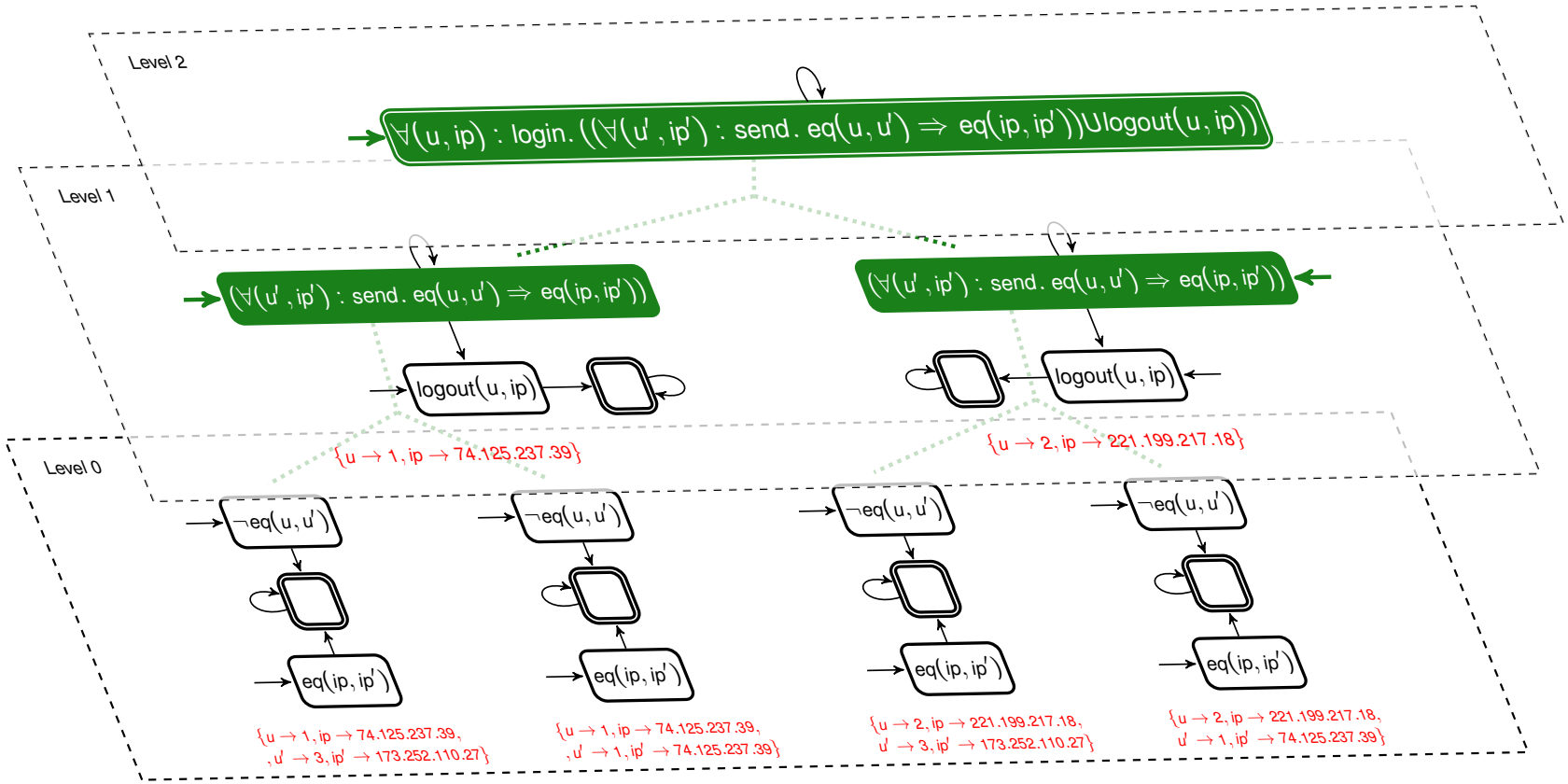

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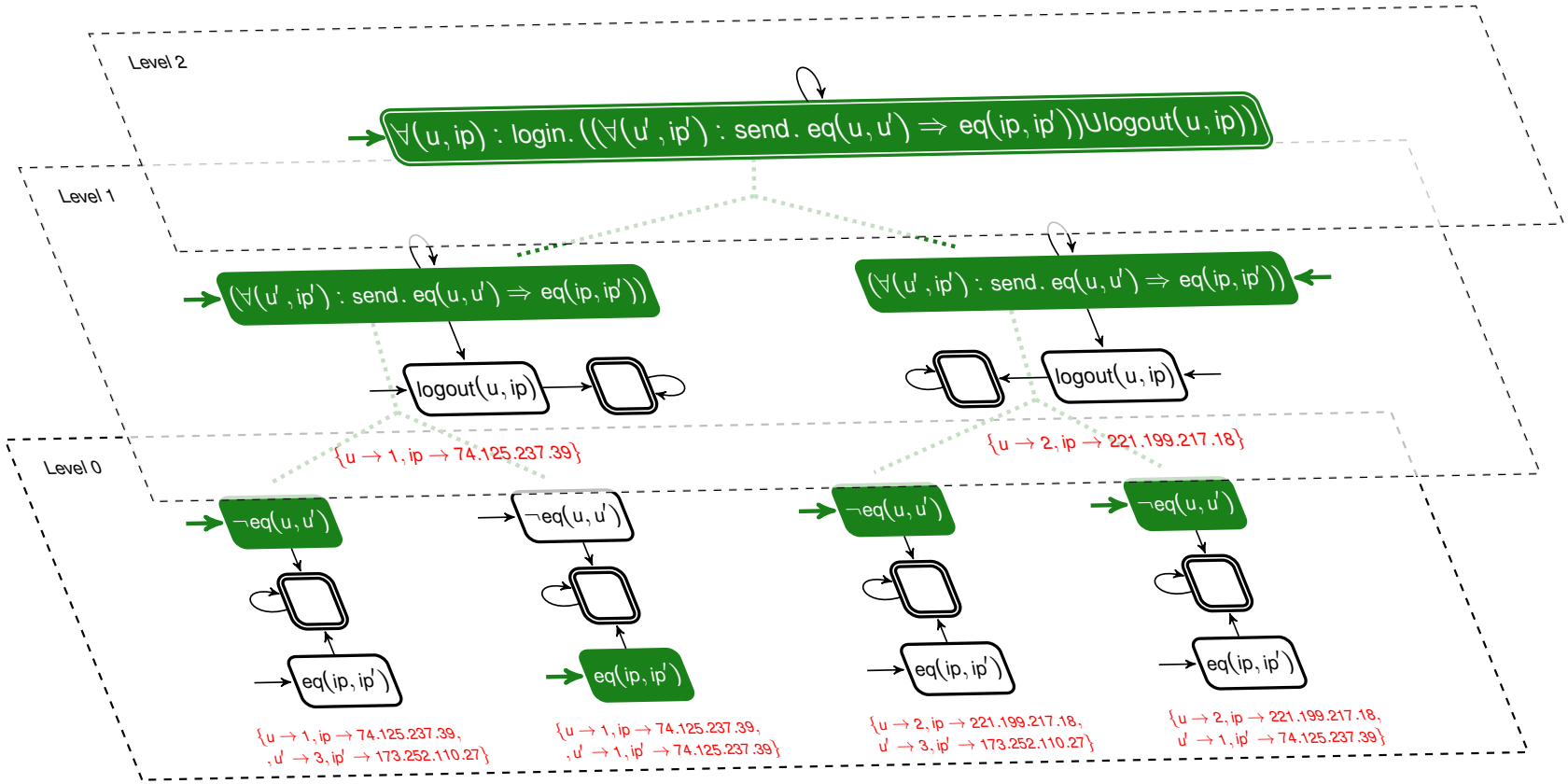

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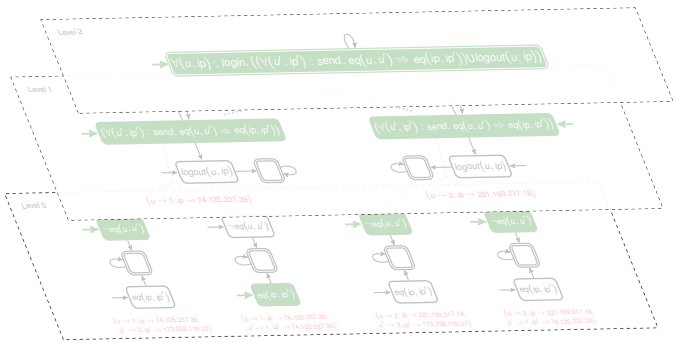

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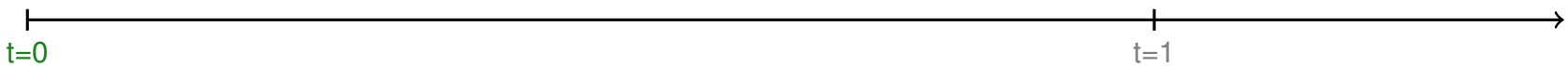

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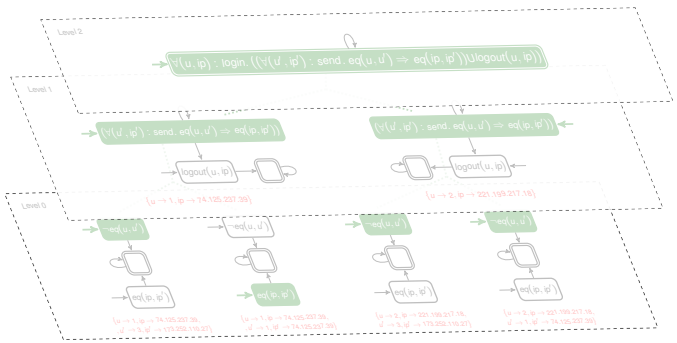

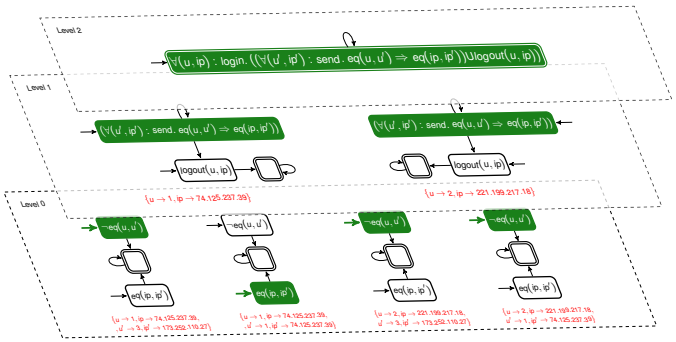

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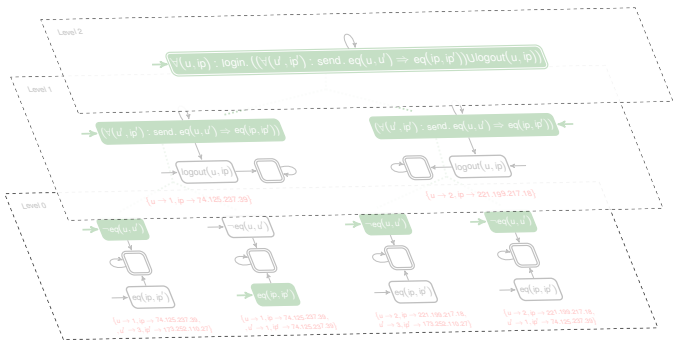
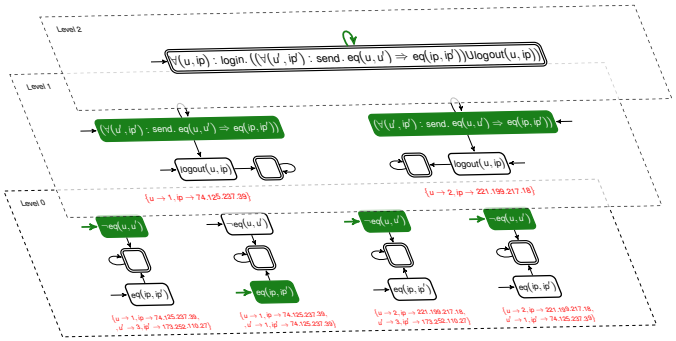
Spawning automaton

Example





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Spawning automaton

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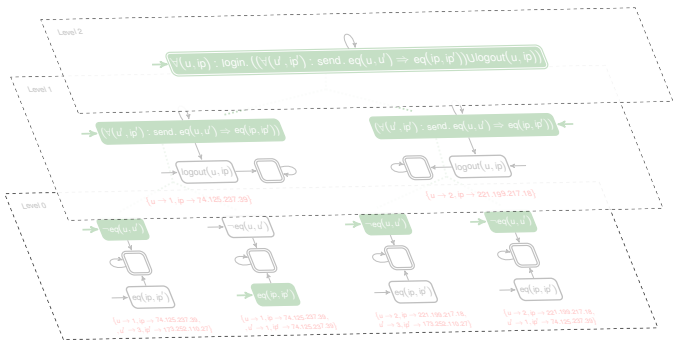

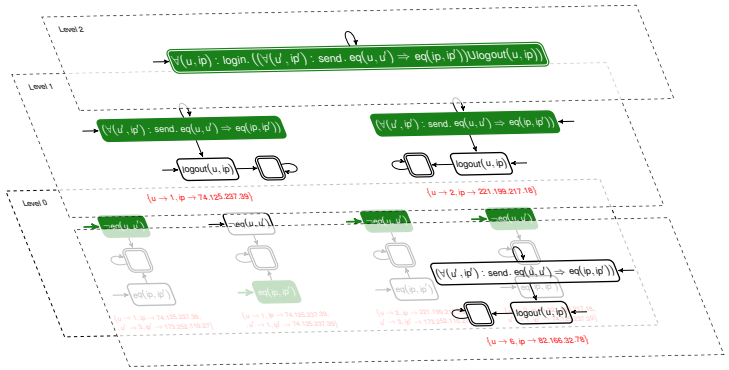

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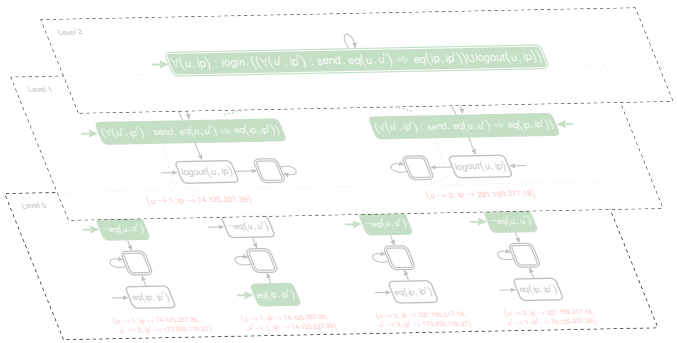

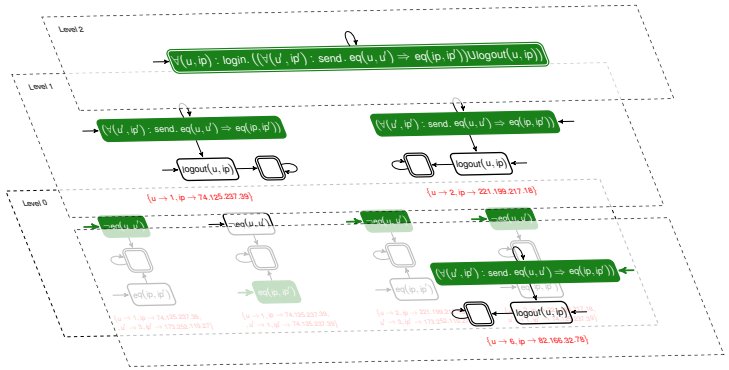

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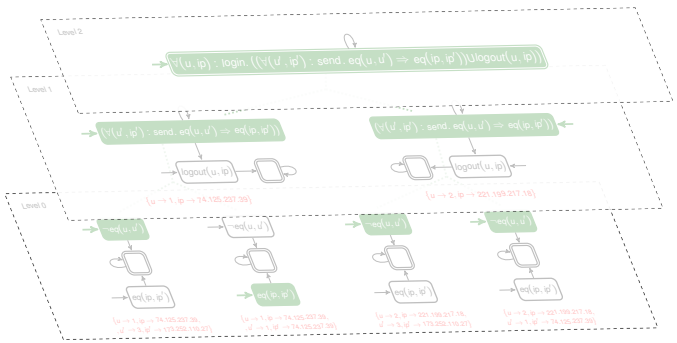

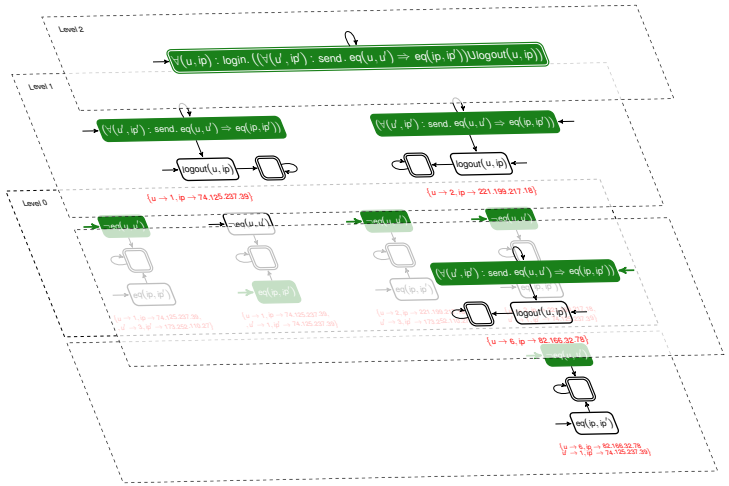

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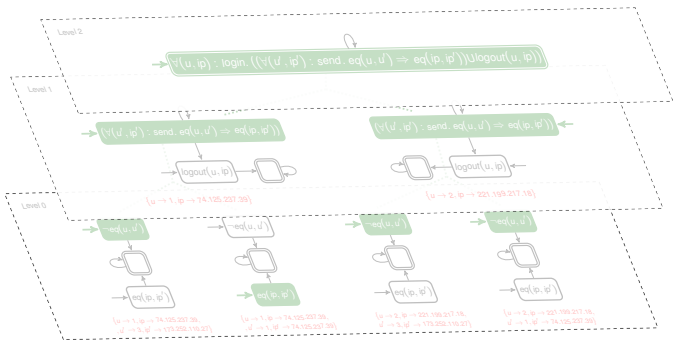

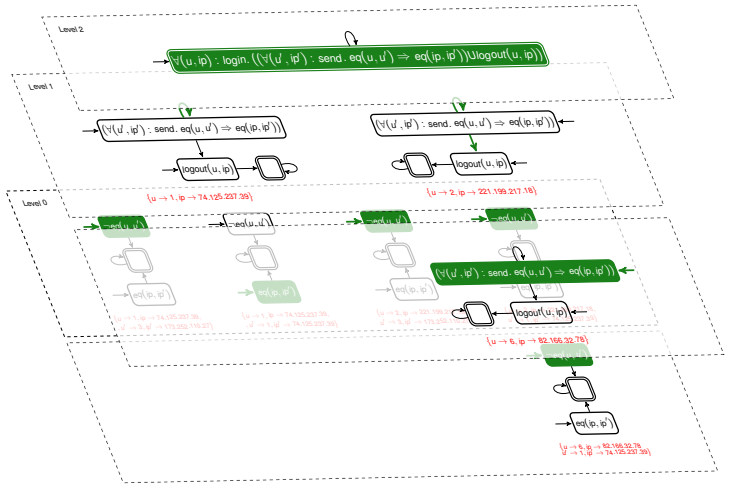

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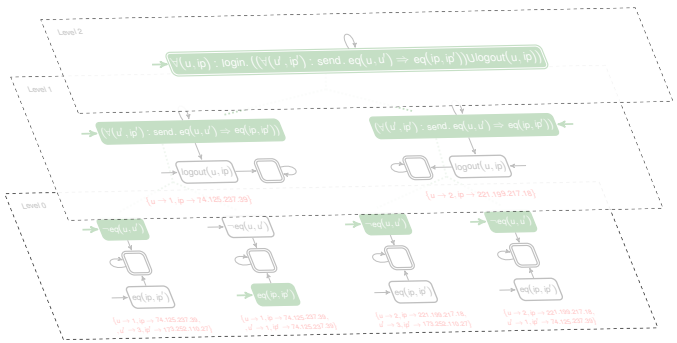

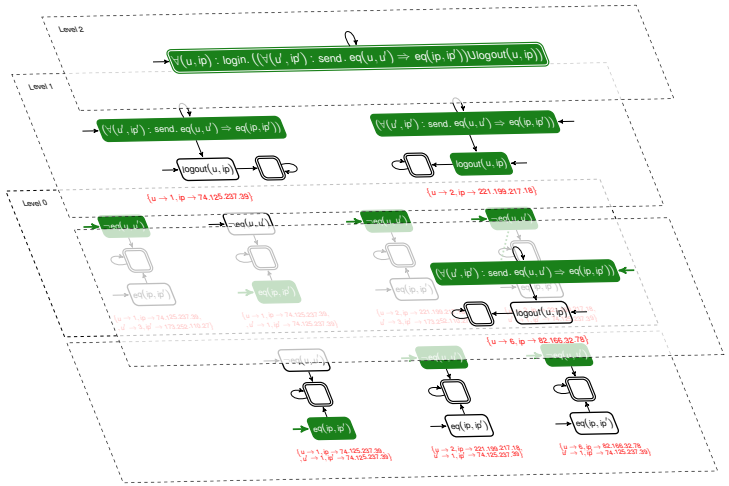

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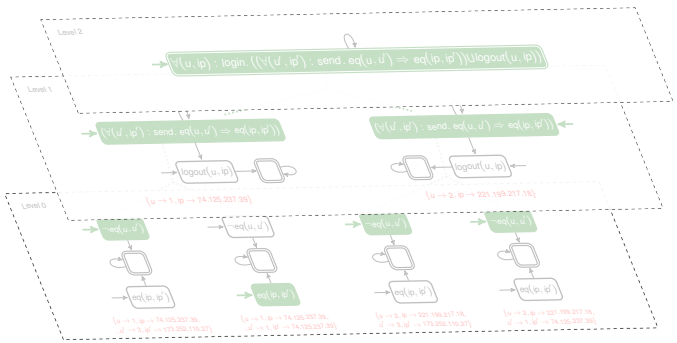

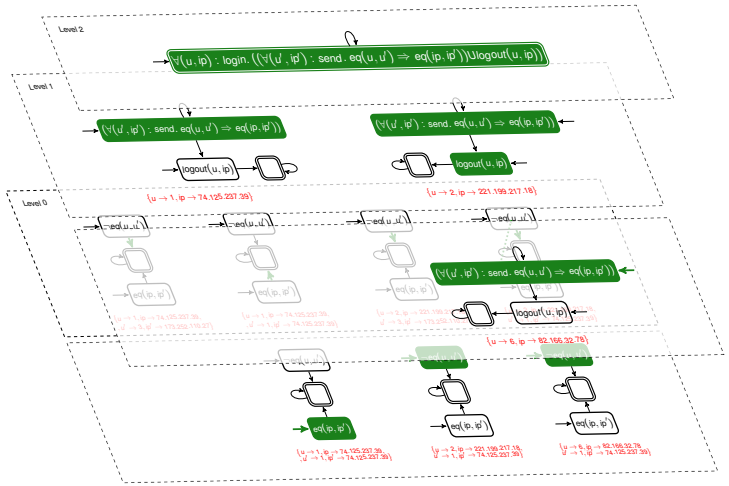

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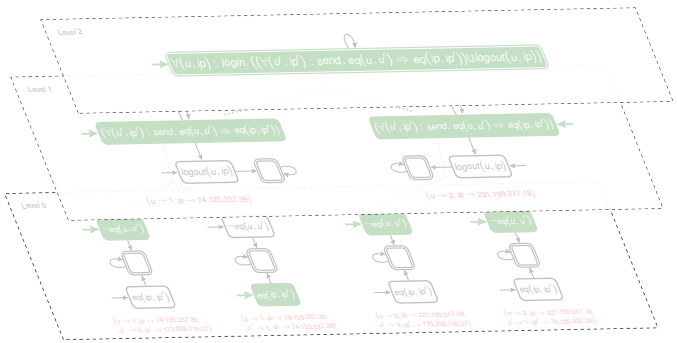
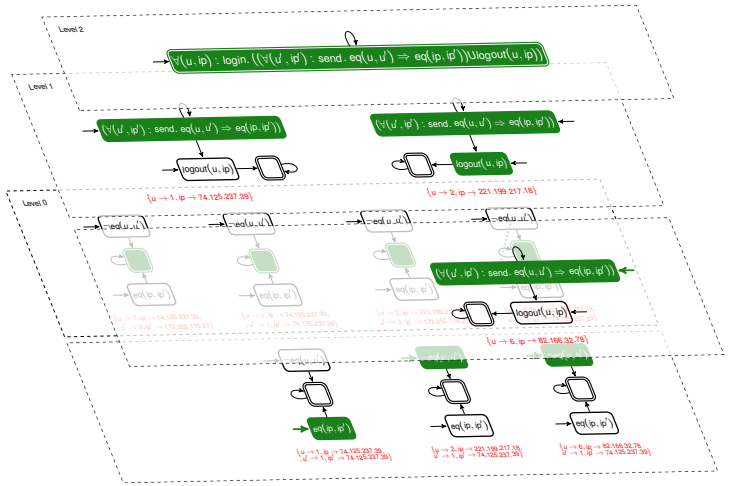
Spawning automaton

Example





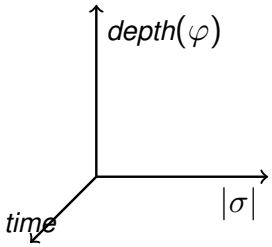
{ *login*(1, 74.125.237.39),
login(2, 221.199.217.18),
send(3, 173.252.110.27),
send(1, 74.125.237.39) }

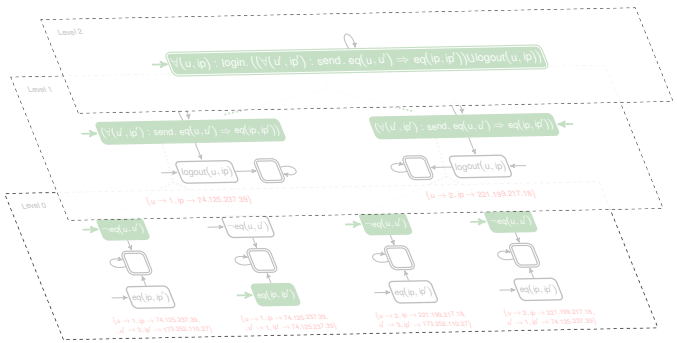
{ *login*(6, 82.166.32.78),
logout(2, 221.199.217.18),
send(1, 74.125.237.39) }

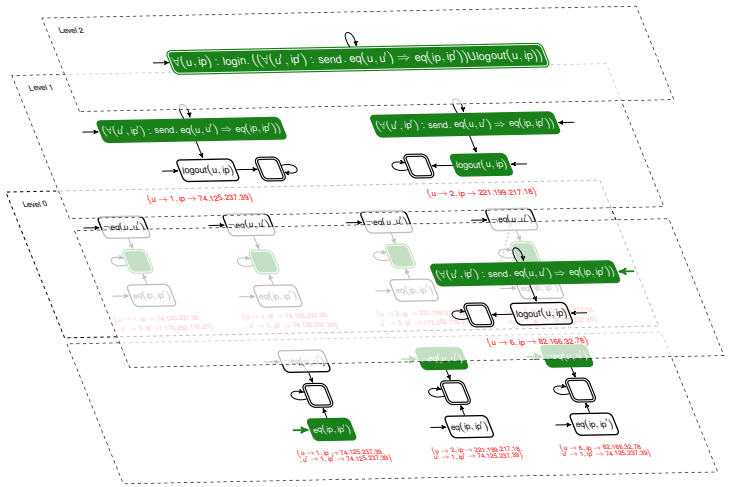
t=0 — t=1

Spawning automaton

Example







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t=0 — t=1

Spawning automaton

Definition

$\mathcal{A} = (\Sigma, Q, Q_0, \delta_{\rightarrow}, \mathcal{F}, \quad)$

- Σ an alphabet
- Q a finite set of states.
- $Q_0 \subseteq Q$ a set of distinguished initial states.
- $\delta_{\rightarrow} : Q \times \Sigma \longrightarrow 2^Q$ a transition relation.
- $\mathcal{F} = \{F_1, \ldots, F_n \mid F_i \subseteq Q\}$ an acceptance condition.

Spawning automaton

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- $\ell \in \mathbb{N}_0$ is the level of $\mathcal{A}$.
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Spawning automaton

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- $\ell \in \mathbb{N}_0$ is the level of $\mathcal{A}$.
- $\delta_{\downarrow} : Q \times \Sigma \longrightarrow \mathcal{B}^+(\mathcal{A}^{<\ell})$ a spawning function.

Constructing $\delta_{\downarrow}^{\varphi}$ for $\varphi \in \mathrm{LTL}^{\mathrm{FO}}$

$$\delta_{\downarrow}(q, (\mathfrak{A}, \sigma)) = \left(\bigwedge_{\forall \mathbf{x}:p.\psi \in q} \left(\bigwedge_{(p,\mathbf{d}) \in \sigma} \mathcal{A}_{\psi, v(\mathbf{x},\mathbf{d})} \right) \right) \wedge \left(\bigwedge_{\neg \forall \mathbf{x}:p.\psi \in q} \left(\bigvee_{(p,\mathbf{d}) \in \sigma} \mathcal{A}_{\neg\psi, v(\mathbf{x},\mathbf{d})} \right) \right)$$

Spawning automaton

When is a run accepting?

Local acceptance (= Büchi acceptance)

$\mathcal{A}$ accepts exactly those runs in which the set of infinitely often occurring states contains at least a state from each $F_1, \ldots, F_n$.

(Global) acceptance

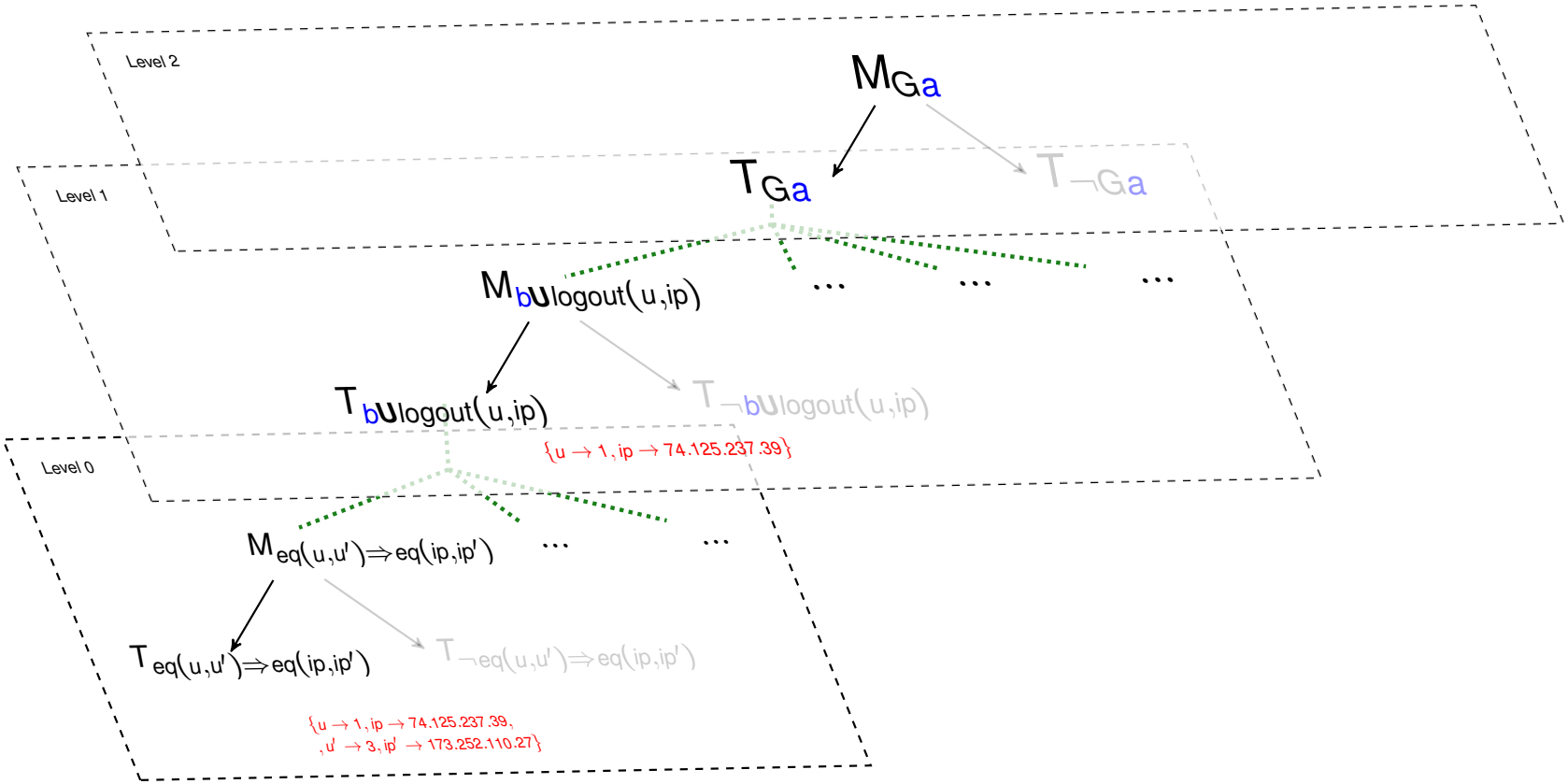
- if $\ell = 0$: local acceptance = acceptance
- if $\ell > 0$: run is local accepting and for all $i \in \mathbb{N}_0$ there is a set $Y \subseteq \mathcal{A}^{<\ell}$, s.t. $Y \models \delta_{\downarrow}(\rho(i), w_i)$ and all $\mathcal{A} \in Y$ have an accepting run over w^i.

Monitor

$$M_\varphi(\overline{\mathfrak{A}}, u) = \top \Rightarrow (\overline{\mathfrak{A}}, u) \in \mathsf{good}(\varphi)$$

(resp. for $\bot$ and $\mathsf{bad}(\varphi)$)

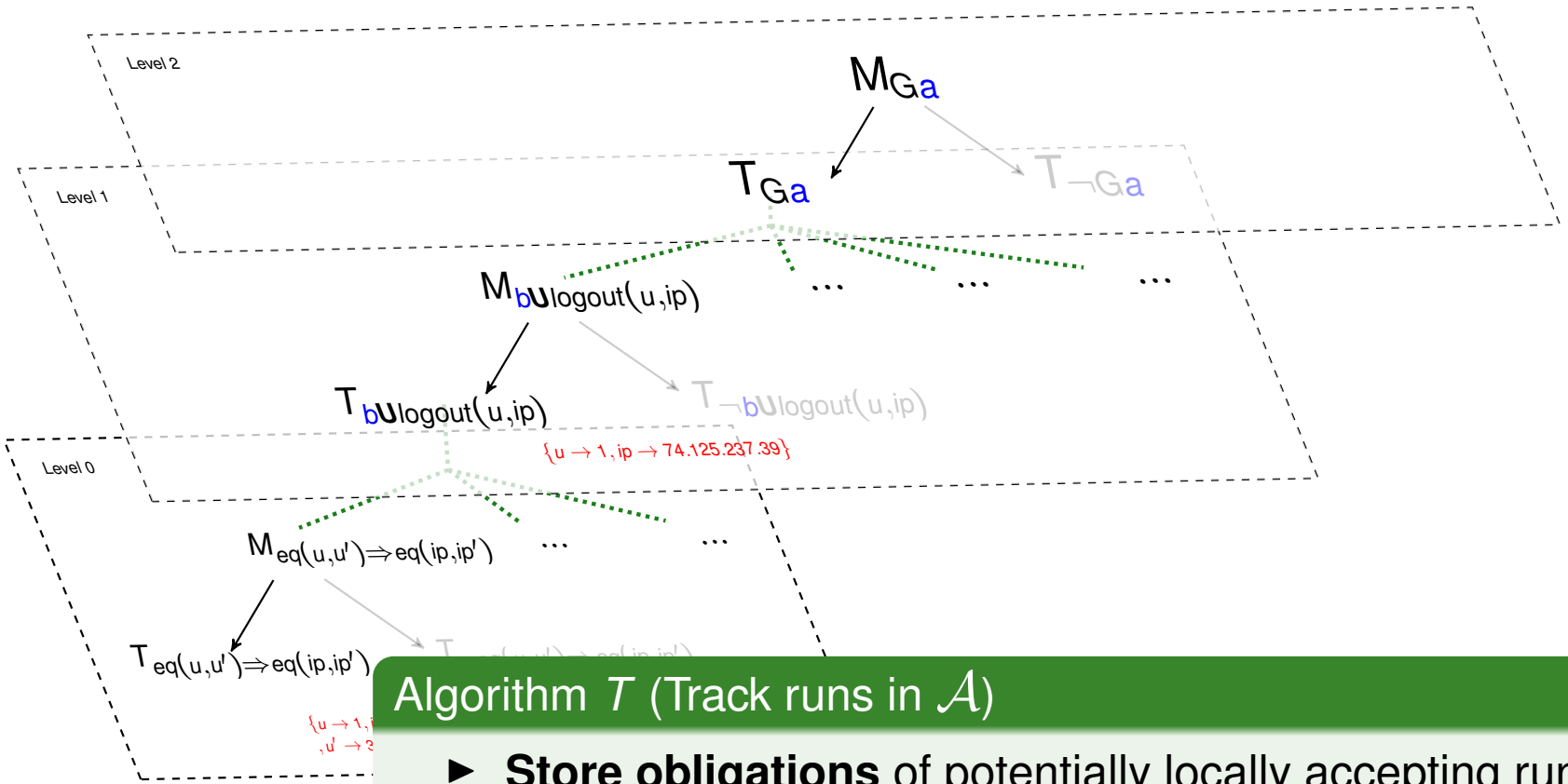
A monitor for LTL^{FO}



Algorithm *M* (Monitor)

- **Create** two instances of **Algorithm T** (for φ and $\neg\varphi$)
- **Forward event** to $T_{\varphi,v}$ and $T_{\neg\varphi,v}$
- **Return** $\bot$ (resp. $\top$) **if** $T_{\varphi,v}$ (resp. $T_{\neg\varphi,v}$) has **"no runs"**, **otherwise print "?"**

A monitor for LTL^{FO}



Algorithm T (Track runs in $\mathcal{A}$)

- **Store obligations** of potentially locally accepting runs: $\{[\ldots, \delta_{\downarrow}(\rho(i), \sigma_i), \ldots], \ldots\}$
- **Execute** M for each $\mathcal{A}$ in $\delta_{\downarrow}(\rho(i), \sigma_i)$ and **wait for result**
- **Remove runs** if $\delta_{\downarrow}(\rho(i), \sigma_i) = \bot$
- **Remove obligations** if $\delta_{\downarrow}(\rho(i), \sigma_i) = \top$

Monitor properties

Trace-length independence

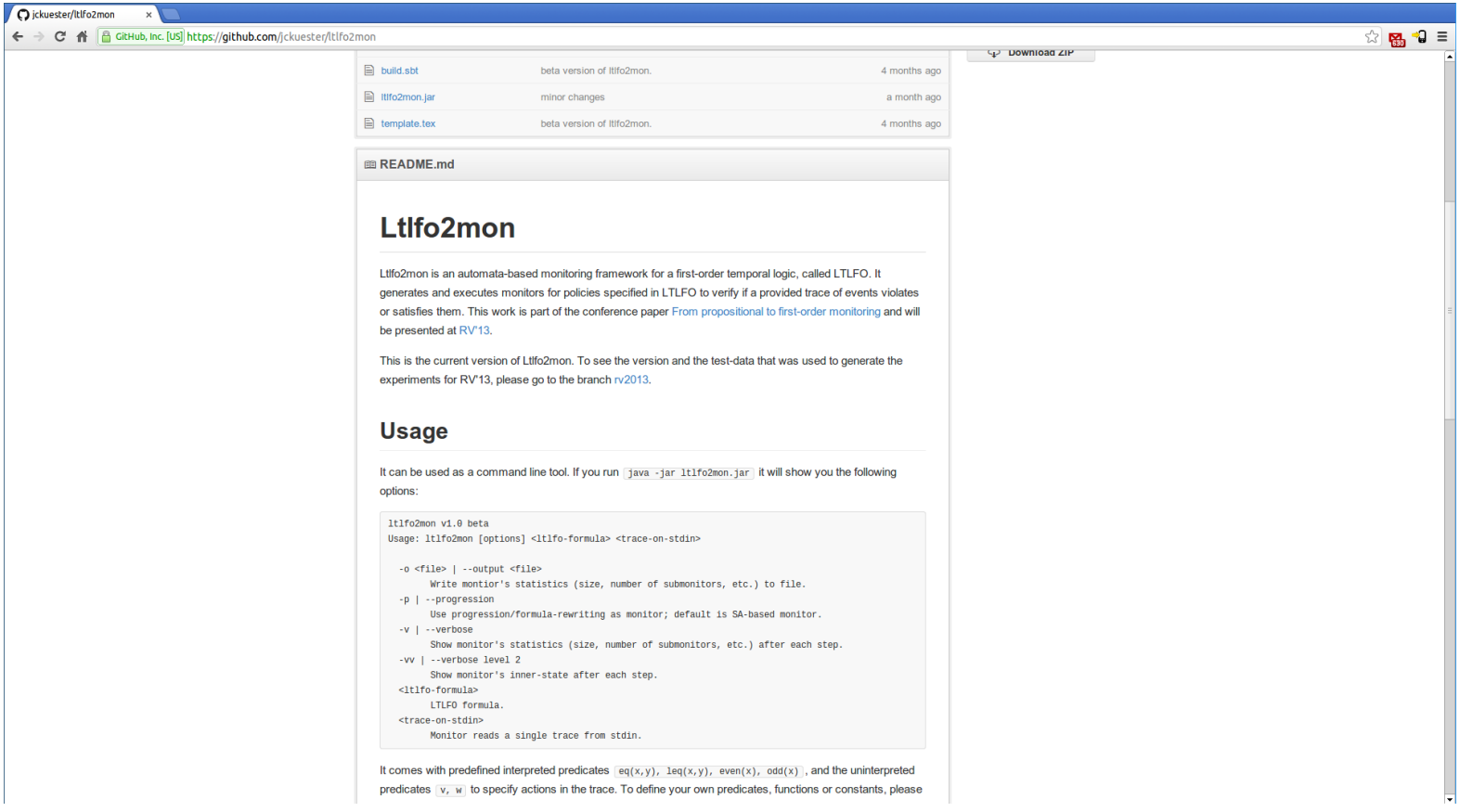
- If a formula is not trace-length dependent, then the monitor is trace-length independent.
- Effciency does not decline with an increasing number of observations.

Monotonic

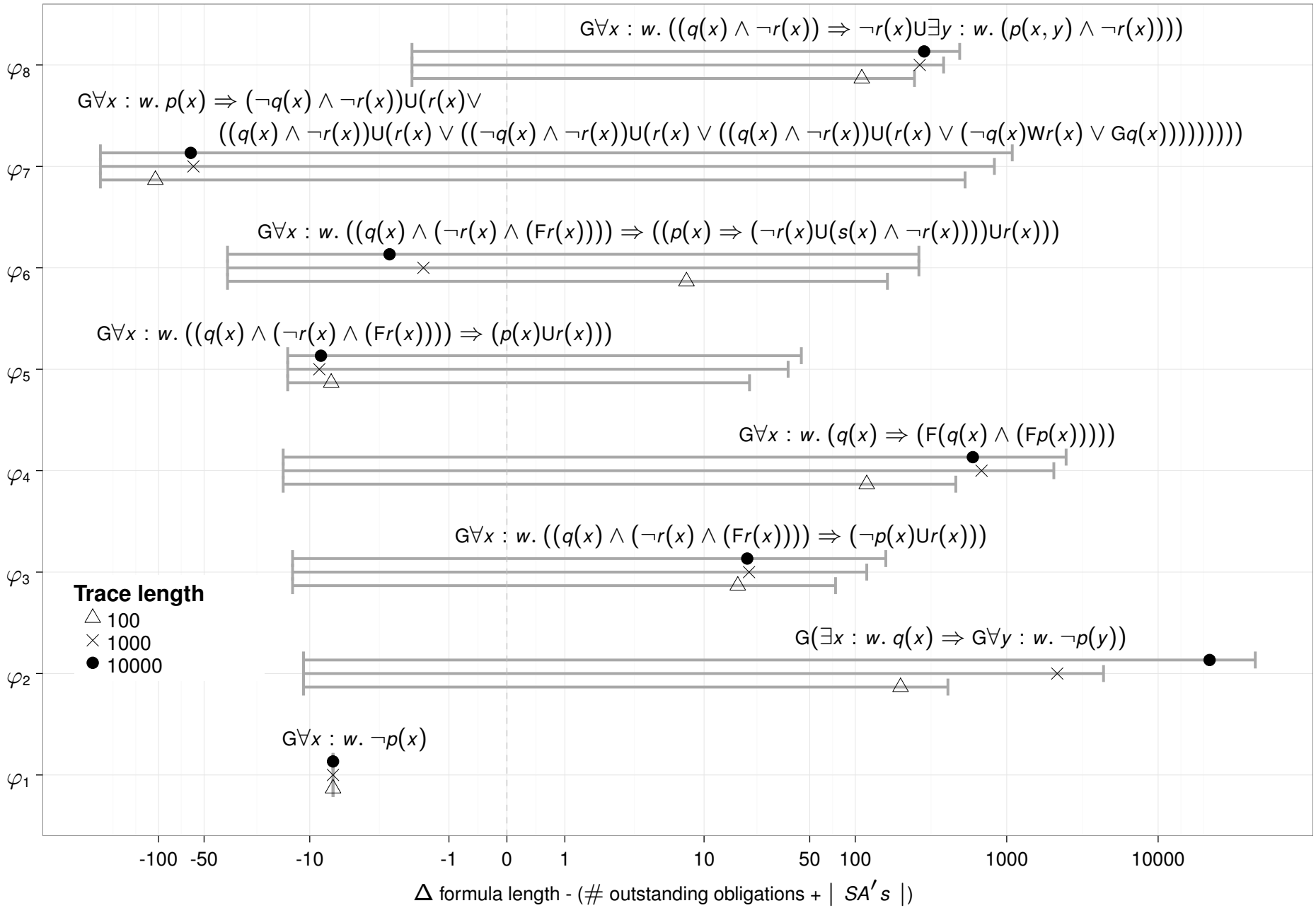
- Once the monitor **returns** $\bot$ to the user, i.e., has **found a bad prefix**, additional observations do not lead to it **returning** $\top$ (and vice versa).

Tool: Ltlfo2Mon

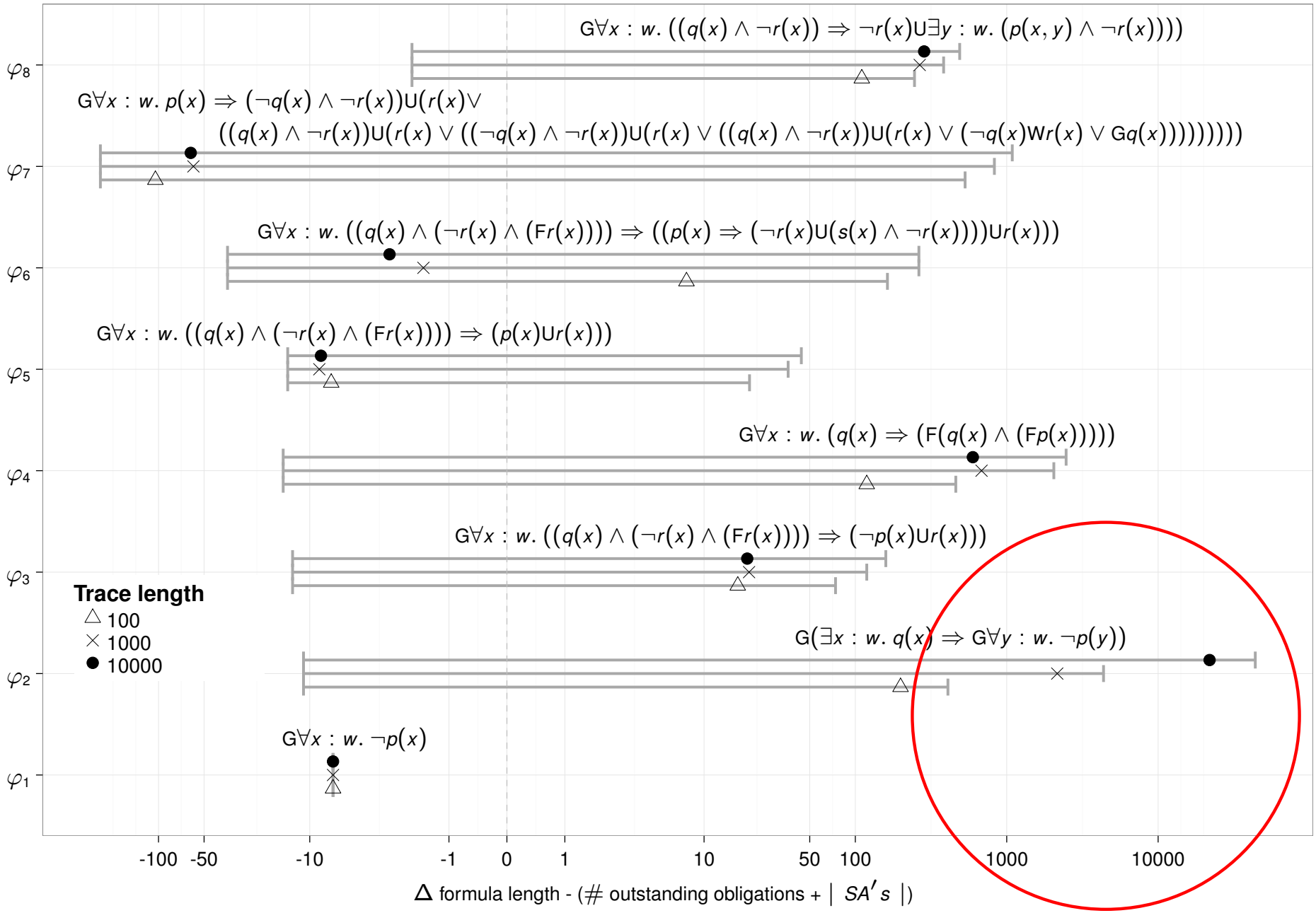
https://github.com/jckuester/ltlfo2mon



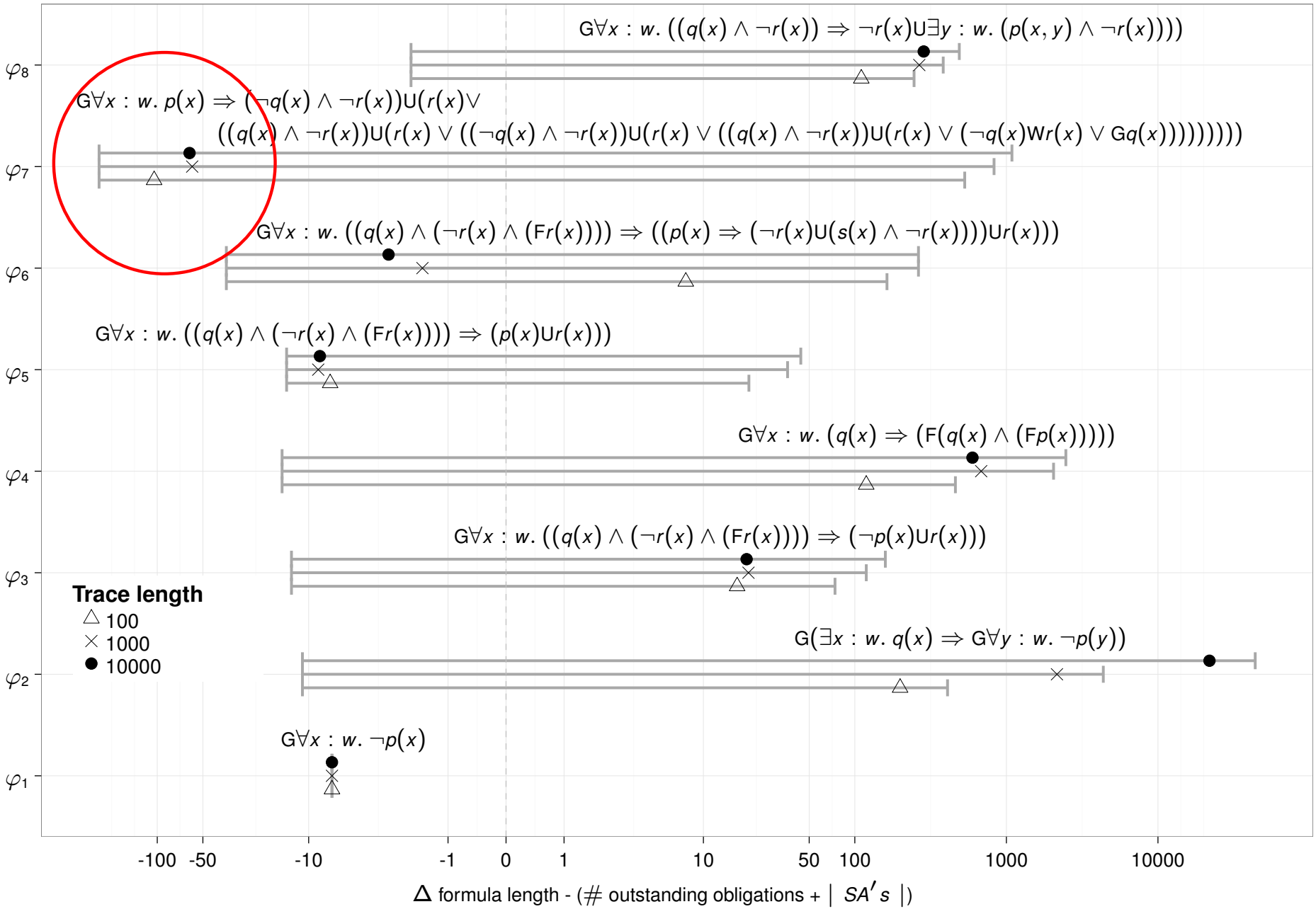
SA-based monitor vs. formula rewriting



SA-based monitor vs. formula rewriting



SA-based monitor vs. formula rewriting



Complexity results: LTL vs. LTL^{FO}

	Satisfiability	**Word problem**	**Model checking**	**Prefix problem**
LTL	PSpace-complete	$<$ Bilinear-time	PSpace-complete	PSpace-complete

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	Satisfiability	**Word problem**	**Model checking**	**Prefix problem**
LTL	PSpace-complete	$<$ Bilinear-time	PSpace-complete	PSpace-complete
LTL^{FO}	Undecidable	PSpace-complete	ExpSpace-membership, PSpace-hard	Undecidable

Summary

- A first-order temporal logic, called LTL^{FO}, suitable for reasoning about systems with data at runtime.
- New automaton model called spawning automaton.
- Monitor algorithm for LTL^{FO} based on spawning automaton.
  - https://github.com/jckuester/ltlfo2mon
- Complexity results LTL vs. LTL^{FO}