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ESORICS

Real-time Policy Enforcement with Metric First-Order Temporal Logic

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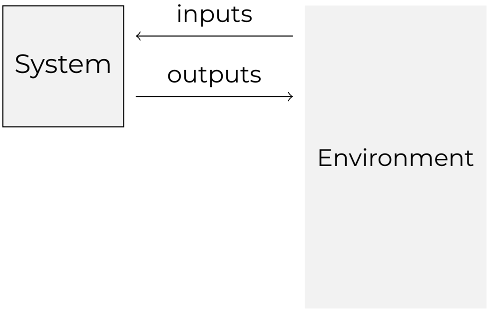
François Hublet · David Basin · Srđan Krstić

francois.hublet@inf.ethz.ch · basin@inf.ethz.ch · srdan.krstic@inf.ethz.ch

Institute of Information Security, Department of Computer Science, ETH Zürich

Runtime enforcement



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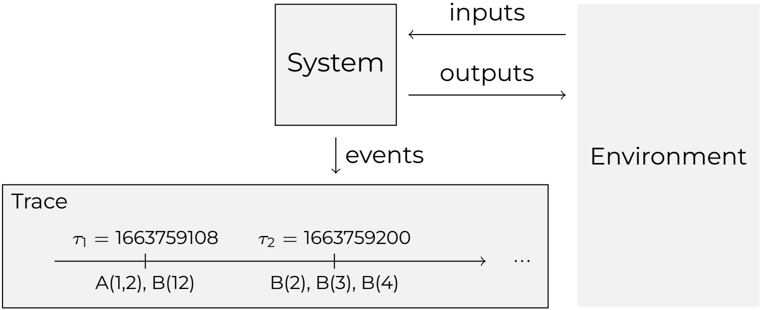

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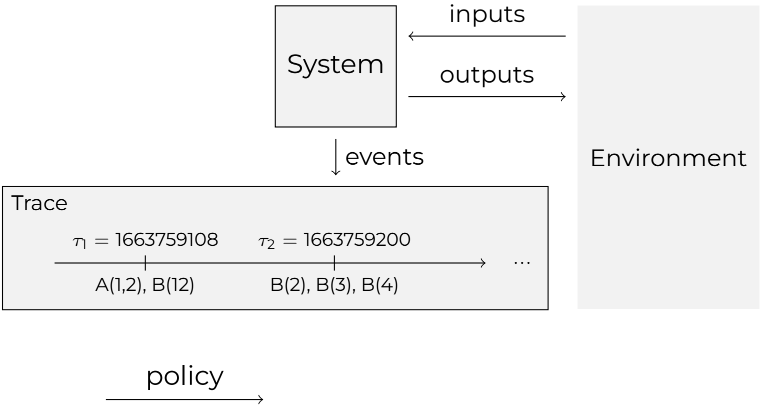

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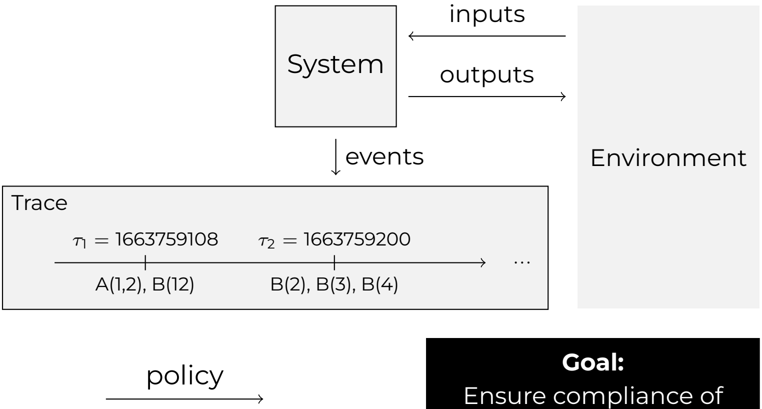

Goal:
Ensure compliance of the system's behavior with the policy

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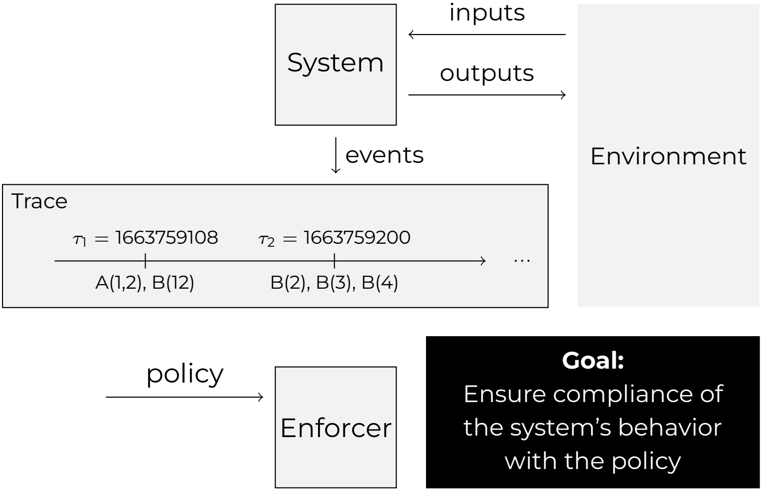

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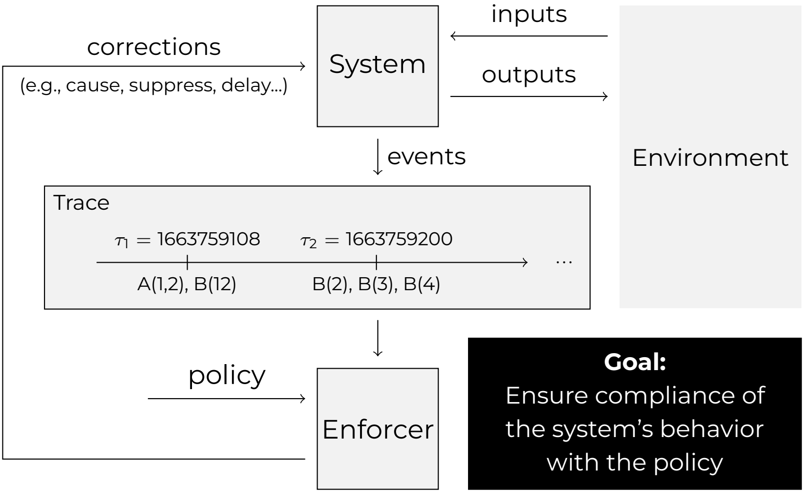

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Metric First-Order Temporal Logic (MFOTL)

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"At any time, for all x and y, if $\mathrm{A}(x, y)$ has occurred in the last 1000 seconds, then $\mathrm{B}(y)$ must occur now"

$$\Box\, [\forall x, y.\ (\blacklozenge_{[0,1000]} \mathrm{A}(x, y)) \Rightarrow \mathrm{B}(y)]$$

Runtime enforcement with MFOTL

Existing enforcement tools do not support MFOTL

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  - Security automata (GREP [6], TiPEX [7]...)

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Focus: Enforcement of MFOTL policies

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1. **Characterization** of enforceable MFOTL policies

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3. First MFOTL enforcement **tool**

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Runtime enforcement setup

Signature	$\Sigma = (\mathbb{D}, \mathbb{E}, a)$	domain $\mathbb{D}$, event names $\mathbb{E}$, arities $a : \mathbb{E} \to \mathbb{N}$
Events	$e(d_1, \ldots, d_{a(e)}) \in \mathrm{Ev}$	$e \in \mathbb{E}$, $d_i \in \mathbb{D}$
Databases	$D = \{e_1, ..., e_k\} \in \mathbb{DB}$	$e_i \in \mathrm{Ev}$
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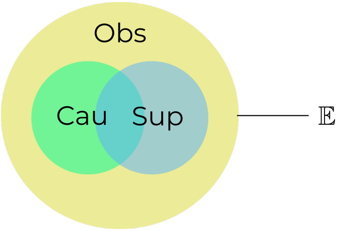

We distinguish:

- *suppressable* (Sup) vs. *causable* (Cau) events [8]
- controllable (Sup ∪ Cau) vs. *only-observable* (Obs) events [9]

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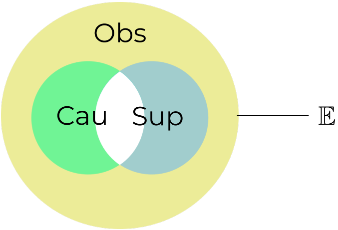

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- *suppressable* (Sup) vs. *causable* (Cau) events [8]
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Additional assumption: $\mathrm{Sup} \cap \mathrm{Cau} = \emptyset$

Metric First-Order Temporal Logic

Syntax

MFOTL is defined by the grammar

$$\varphi ::= r(t_1, \ldots, t_{a(r)}) \mid \neg\varphi \mid \varphi \lor \varphi \mid \exists x.\, \varphi$$
$$\mid \underbrace{\bullet_I}_{\text{“previous”}} \varphi \mid \underbrace{\bigcirc_I}_{\text{“next”}} \varphi \mid \varphi \underbrace{\mathsf{S}_I}_{\text{“since”}} \varphi \mid \varphi \underbrace{\mathsf{U}_I}_{\text{“until”}} \varphi$$

with $r \in \mathbb{E}$, V variables, $t_i \in V \cup \mathbb{D}$, $I \subseteq \{[a, b) \mid (a, b) \in \mathbb{N}^2, b > a\}$.

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The trace property specified by φ is $\mathcal{L}(\varphi) := \{\sigma \mid \emptyset, 1 \vDash_\sigma \varphi\}$

Metric First-Order Temporal Logic

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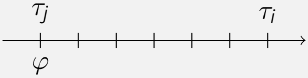
$v, i \models_\sigma \blacklozenge_I \varphi \iff \exists j.\ \sigma =$



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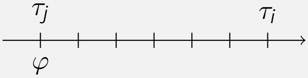

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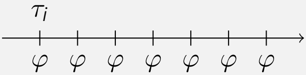

$\cdots$

MFOTL for enforcement

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Consider only (safety) policies of the form $\Box\, \varphi$

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Consider only (safety) policies of the form $\Box\,\varphi$

+ for practical enforcement

φ *future-free* ($\approx$ independent of the future)

$\text{MFOTL}^{\mathcal{F}}_{\Box} := \{\Box\,\varphi \mid \varphi \text{ future free}\}$

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Example

Assume $\mathsf{B} \in \mathsf{Cau}$.

The policy $\Box[\forall x, y.\ \blacklozenge_{[0,1000]} \mathsf{A}(x, y) \Rightarrow \mathsf{B}(y)]$ is enforceable.

MFOTL: negative result

Question

Is there an algorithm to decide if an $\text{MFOTL}^{\mathcal{F}}_{\square}$ policy is enforceable?

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Theorem 1

Assume that Sup contains an event of arity > 1 and Obs $\neq \emptyset$. The set $\{\varphi \in \text{MFOTL}^{\mathcal{F}}_{\square} \mid \varphi \text{ is enforceable}\}$ is not computable.

MFOTL: negative result

Question

Is there an algorithm to decide if an $\text{MFOTL}^{\mathcal{F}}_{\Box}$ policy is enforceable?

Theorem 1

Assume that Sup contains an event of arity > 1 and Obs $\neq \emptyset$.
The set $\{\varphi \in \text{MFOTL}^{\mathcal{F}}_{\Box} \mid \varphi \text{ is enforceable}\}$ is not computable.

Proof: Reduction to the Entscheidungsproblem of FOL.

MFOTL: positive result

Define *guarded MFOTL* (GMFOTL) as

$$\psi ::= \bot \mid s(t_1, \ldots, t_n) \mid \neg c(t_1, \ldots, t_n) \mid \psi \wedge \varphi \mid \psi \vee \psi \mid \exists x.\, \psi$$

where $s \in \mathsf{Sup}, c \in \mathsf{Cau}$, and $\varphi \in \mathsf{MFOTL}$.

Lemma

For all $\psi \in \mathsf{GMFOTL}$, $\Box \neg \psi$ is enforceable.

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Lemma

For all $\psi \in$ GMFOTL, $\Box \neg\psi$ is enforceable.

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$\varphi \in \text{MFOTL}^{\mathcal{F}}_{\Box}$ is enforceable $\Longleftrightarrow \exists \psi \in$ GMFOTL. $\varphi \equiv \Box \neg\psi$.

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$$\Box[\forall x, y.\ \blacklozenge_{[0,1000]} \mathrm{A}(x,y) \Rightarrow \mathrm{B}(y)] \equiv \Box[\neg(\underbrace{\exists x, y.\ \neg \mathrm{B}(y) \wedge \blacklozenge_{[0,1000]} \mathrm{A}(x,y)}_{\in \text{GMFOTL}})]$$

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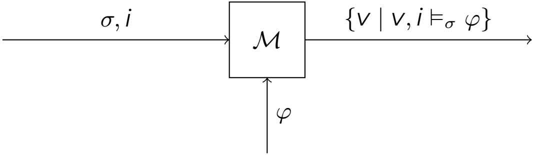

Enforcing MFOTL policies

Example

Consider $\varphi = \Box \neg\psi$ where $\psi = \exists x, y.\ \neg \mathsf{B}(y) \land \blacklozenge_{[0,1000]} \mathsf{A}(x, y)$.

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Enforce φ on $\sigma = (0, \{\mathsf{A}(1, 2), \mathsf{B}(12)\})$.

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\end{aligned}
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Enforcing MFOTL policies

Example

Consider $\varphi = \Box \neg\psi$ where $\psi = \exists x, y.\ \neg B(y) \wedge \blacklozenge_{[0,1000]} A(x, y)$.

Enforce φ on $\sigma = (0, \{A(1, 2), B(12)\})$.

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falsify $\exists x, y.\ \neg \mathsf{B}(y) \wedge \blacklozenge_{[0,1000]} \mathsf{A}(x, y))$ on σ

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$\rightsquigarrow$ falsify $\neg \mathsf{B}(y) \wedge \blacklozenge_{[0,1000]} \mathsf{A}(x, y)$ on σ for $x = 1, y = 2$

$\rightsquigarrow$ make $\neg \mathsf{B}(y)$ false on σ for $x = 1, y = 2$

$\rightsquigarrow$ cause $\mathsf{B}(y) = \mathsf{B}(2)$

Enforcement algorithm

- In general, one top-down iteration is not sufficient (e.g., for $\psi = \neg\mathsf{B}(1) \vee (\neg\mathsf{B}(2) \wedge \mathsf{B}(1))$)

Enforcement algorithm

- In general, one top-down iteration is not sufficient (e.g., for $\psi = \neg$B(1) $\vee$ ($\neg$B(2) $\wedge$ B(1)))
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Enforcement algorithm

- In general, one top-down iteration is not sufficient (e.g., for $\psi = \neg \mathrm{B}(1) \vee (\neg \mathrm{B}(2) \wedge \mathrm{B}(1)))$
- Perform a fixpoint computation
- We prove termination for monitorable and enforceable policies

About the condition $\mathsf{Sup} \cap \mathsf{Cau} = \emptyset$

- Needed for our enforceability condition to hold

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About the condition $\mathsf{Sup} \cap \mathsf{Cau} = \emptyset$

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If $B \in \mathsf{Sup} \cap \mathsf{Cau}$, we have $B(1) \vee \neg B(1) \in \mathsf{GMFOTL}$, but $\square[\neg(B(1) \vee \neg B(1))] = \square \perp$ is not enforceable.

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About the condition $\mathsf{Sup} \cap \mathsf{Cau} = \emptyset$

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If $B \in \mathsf{Sup} \cap \mathsf{Cau}$, we have $B(1) \vee \neg B(1) \in$ GMFOTL, but $\square[\neg(B(1) \vee \neg B(1))] = \square \bot$ is not enforceable.

- Needed for our algorithm to terminate
- Slightly relaxed in the implementation

Table of contents

Implementation

- Extension of Basin et al.'s MonPoly [2]
- Ca. 500 loc OCaml code
- Runtime performance equivalent or better than GREP's [6] on LTL fragment
- Overhead < 50% with respect to MonPoly

https://gitlab.ethz.ch/fhublet/mfotl-enforcement

Conclusion

In this talk, we have seen:

- A **characterization** of enforceable MFOTL policies
- An **algorithm** for enforcing MFOTL policies
- The first enforcement **tool** for MFOTL

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In this talk, we have seen:

- A **characterization** of enforceable MFOTL policies
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Open questions:

- Can we obtain a characterization for the case $\mathsf{Sup} \cap \mathsf{Cau}$?
- If such a characterization does not exist, how can we still extend the supported fragment?

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- For monitorable class of policies of the form $\Box\,\varphi$
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i	1	2
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$\mathsf{A}(c,d)$	$v_{51} = [(1,2)]$	$v_{52} = []$

Runtime verification of MFOTL policies

State-of-the-art algorithm by Basin et al. [10]

- For monitorable class of policies of the form $\Box\,\varphi$
- Based on (finite) table manipulation

Example

$$\neg\varphi = \exists c.\ \underbrace{\exists d.\ \underbrace{\neg \mathrm{B}(d) \land \underbrace{\top\ \mathrm{S}_{[0,\infty)}\ \mathrm{A}(c,d)}_{\psi_3}}_{\psi_2}}_{\psi_1}$$

i	1	2
τ_i	1663759108	1663759200
D_i	A(1,2), B(12)	B(2), B(3), B(4)
$\emptyset, i \models_\sigma \varphi$	✗	✓
$\neg\varphi = \exists c.\ \psi_1$	$v_1 = \pi_{(1)} v_{11} = [()]$	$v_2 = \pi_{(1)} v_{12} = []$
$\psi_1 = \exists d.\ \psi_2$	$v_{11} = \pi_{(1)} v_{21} = [(1)]$	$v_{12} = \pi_{(1)} v_{22} = []$
$\psi_2 = \neg \mathrm{B}(d) \land \psi_3$	$v_{21} = v_{31} \rhd_{(2,1)} v_{41} = [(1,2)]$	$v_{22} = v_{32} \rhd_{(2,1)} v_{42} = []$
$\psi_3 = \top\ \mathrm{S}_{[0,\infty)}\ \mathrm{A}(c,d)$	$v_{31} = v_{51} = [(1,2)]$	$v_{32} = v_{52} \cup v_{31} = [(1,2)]$
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Enforcing MFOTL policies

The idea, in a nutshell:

- Focus on $\Box \neg\varphi$ where $\varphi \in$ GMFOTL
- Use $\mathcal{M}$ as a subroutine
- Compute corrections following the structure top-down

Enforcing MFOTL policies

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Enforcing MFOTL policies

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$\psi_1 = \exists d.\ \psi_2$	$v_{11} = [(1)]$	$\text{enf}(\psi_1, \sigma, (1)) = \text{enf}(\psi_2, \sigma, (1,2))$
$\psi_2 = \neg\text{B}(d) \wedge \psi_3$	$v_{21} = [(1,2)]$	$\text{enf}(\psi_2, \sigma, (1,2)) = \text{enf}(\neg\text{B}(d), \sigma, (2))$
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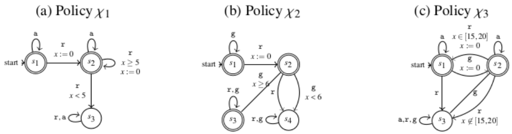
$$\begin{aligned}
\mathsf{enf}(\neg\varphi, \sigma, ()) &= \mathsf{enf}(\psi_1, \sigma, (1)) \\
\mathsf{enf}(\psi_1, \sigma, (1)) &= \mathsf{enf}(\psi_2, \sigma, (1,2)) \\
\mathsf{enf}(\psi_2, \sigma, (1,2)) &= \mathsf{enf}(\neg \mathsf{B}(d), \sigma, (2)) \\
&= (\emptyset, \{B(2)\})
\end{aligned}$$

Performance



$\chi_1 = \Box\neg(\mathtt{r} \wedge ((\blacklozenge_{[1,5)}\mathtt{r}) \vee (\bullet_{[0,0]}\blacklozenge_{[0,0]}\mathtt{r})))$ Sup $= \{\mathtt{r}\}$, Obs $= \{\mathtt{a}\}$

$\chi_2 = \Box\neg((\mathtt{g} \wedge \blacklozenge_{[0,6)}(\mathtt{r} \wedge (\neg\bullet\blacklozenge\mathtt{r}))) \vee (\mathtt{r} \wedge (\bullet(\neg\mathtt{g}\,\mathsf{S}\,(\mathtt{r} \wedge (\neg\bullet\blacklozenge\mathtt{r}))))))$ Sup $= \{\mathtt{r},\mathtt{g}\}$, Obs $= \emptyset$

$\chi_3 = \Box\neg(\mathtt{r} \wedge ((\neg\mathtt{r}\,\mathsf{S}_{(20,\infty)}\,\mathtt{g}) \vee (\neg\mathtt{r}\,\mathsf{S}_{[0,15)}\,\mathtt{g}) \vee (\neg\mathtt{g}\,\mathsf{S}\,\mathtt{r})) \vee \mathtt{g} \wedge \neg\mathtt{r}\,\mathsf{S}\,\mathtt{g})$ Sup $= \{\mathtt{r},\mathtt{g}\}$, Obs $= \{\mathtt{a}\}$

Fig. 3: Policies used to compare EnfPoly to GREP