Monitoring Hyperproperties

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Hyperproperties

Definition

A Hyperproperty $H \subseteq 2^{TR}$ is a set of sets of execution traces [Clarkson, Schneider, '10].

Example

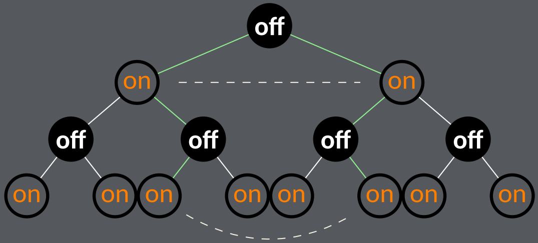
trace equality: "All traces agree on a proposition p."
observational determinism: "A program appears deterministic to low security users."
noninterference, generalized noninterference, noninference, declassification, ...

A Logical Approach to Information-Flow Control

HyperLTL [Clarkson, Finkbeiner, Koleini, Micinski, Rabe, Sánchez, '14]

HyperLTL

- LTL + explicit trace quantification:
  $\exists\pi.\exists\pi'.\ \Box on_\pi \wedge \Box\neg on_{\pi'}$
  satisfiable by $\{\{on\}^\omega, \{off\}^\omega\}$
- trace equality:
  $\forall\pi.\ \forall\pi'.\ \Box(on_\pi \leftrightarrow on_{\pi'})$
- observational determinism:
  $\forall\pi.\ \forall\pi'.\ (O_\pi = O_{\pi'})\ \mathcal{W}\ (I_\pi \neq I_{\pi'})$



Monitoring Hyperproperties

- we sequentially observe traces of a system
- when a new trace comes in, we check whether a given hyperproperty still holds

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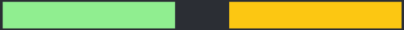

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Overview

1. monitor construction
2. two techniques to make monitoring of hyperproperties feasible in practice:
   - Trace Analysis: exploits a dominance relation between traces
   - Specification Analysis: exploits symmetry, transitivity, and reflexivity in the specification

Monitor Construction

- conference management system with author and pc traces
- no paper submission is lost:
  - every submission (s) is visible (v) to every pc member
  - when comparing two pc traces, they have to agree on v

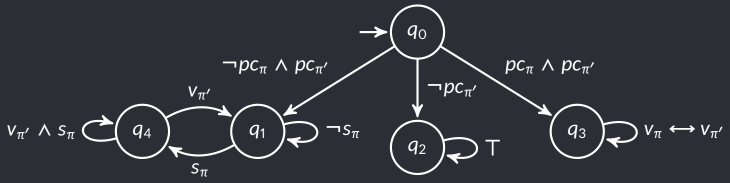
$$\forall \pi.\ \forall \pi'.\ (\neg pc_\pi \wedge pc_{\pi'}) \rightarrow \bigcirc\square(s_\pi \rightarrow \bigcirc v_{\pi'}) \wedge \tag{1}$$

$$(pc_\pi \wedge pc_{\pi'}) \rightarrow \bigcirc\square(v_\pi \leftrightarrow v_{\pi'}) \tag{2}$$

Monitor Construction

$$\forall \pi.\ \forall \pi'.\ (\neg pc_\pi \wedge pc_{\pi'}) \rightarrow \bigcirc \Box (s_\pi \rightarrow \bigcirc v_{\pi'}) \wedge$$
$$(pc_\pi \wedge pc_{\pi'}) \rightarrow \bigcirc \Box (v_\pi \leftrightarrow v_{\pi'})$$

$$\Downarrow$$



Monitor Construction

Deterministic monitor template $\mathscr{M} = (\Sigma, Q, \delta, q_0)$:

- finite alphabet $\Sigma = 2^{AP \times \mathscr{V}}$

The automaton runs in parallel over n-ary tuple $N \in ((2^{AP})^*)^n$ of finite traces:

$$\delta\left(q_i, \bigcup_{j=1}^{n} \bigcup_{a \in N(j)(i)} \{(a, \pi_j)\}\right) = q_{i+1} \quad .$$

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Memory Explosion

The naive approach always stores every trace seen so far!

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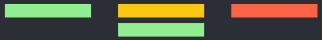

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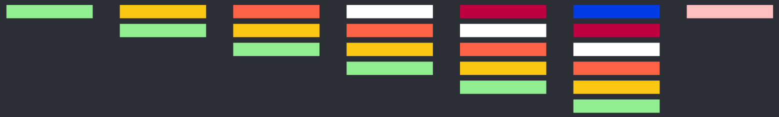

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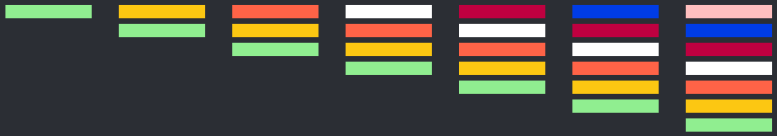

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Trace Analysis: discard traces that are dominated by other traces

Trace Analysis - Example

{}	{s}	{}	{}	{}
{}	{}	{s}	{}	{}

an author submits a paper

another author submits a paper

Trace Analysis - Example

{}	{s}	{}	{}	{}
{}	{}	{s}	{}	{}
{}	{}	{s}	{s}	{}

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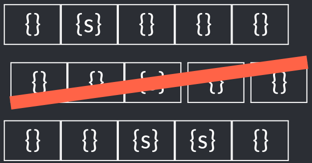
an author submits two papers

Trace Analysis - Example



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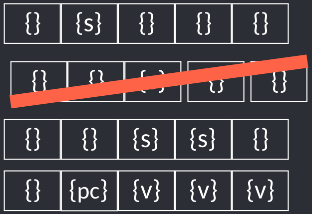

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a pc observes 3 submissions

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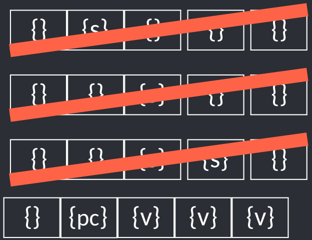

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Trace Analysis - Example

{}	{pc}	{v}	{v}	{v}

a pc member observes three submissions

Trace Analysis - Example

{}	{pc}	{v}	{v}	{v}
{}	{pc}	{v}	{v}	{}

a pc member observes three submissions

↯ a pc member observes two submissions ↯

Trace Analysis

Definition (Trace Redundancy)

- HyperLTL formula φ
- trace set T

a trace t is (T, φ)-redundant if

$$T \text{ is a model of } \varphi \quad \text{if and only if} \quad T \cup \{t\} \text{ is a model of } \varphi$$

Dominance Checking

- HyperLTL formula φ
- traces t and t'
- monitor template $\mathscr{M}_\varphi$

t' dominates t if and only if $\bigwedge_{\pi \in \mathcal{V}} \mathscr{L}(\mathscr{M}_\varphi[t'/\pi]) \subseteq \mathscr{L}(\mathscr{M}_\varphi[t/\pi])$

Storage Minimization Algorithm

input : HyperLTL formula φ, redundancy free trace set T, trace t
output : redundancy free set of traces $T_{min} \subseteq T \cup \{t\}$

$\mathscr{M}_\varphi = \texttt{build\_template}(\varphi)$

```
foreach t′ ∈ T do
    if t′ dominates t then
        return T
    end
end
foreach t′ ∈ T do
    if t dominates t′ then
        T := T \ {t′}
    end
end
return T ∪ {t}
```

Specification Analysis

Basic Idea: We use the HyperLTL-Sat solver EAHyper [Finkbeiner, H., Stenger, ’17] to check whether HyperLTL formulas are symmetric, transitive or reflexive.

- Symmetry: we omit at least half of the monitor instantiations
- Transitivity: we reduce the instantiations to two
- Reflexivity: we omit the reflexive monitor instantiation

Symmetry - Example

For observational determinism

$$\forall \pi. \forall \pi'. (O_\pi = O_{\pi'}) \, W \, (I_\pi \neq I_{\pi'})$$

we check whether the following formula is valid:

$$\forall \pi. \forall \pi'. (O_\pi = O_{\pi'}) \, W \, (I_\pi \neq I_{\pi'}) \\ \longleftrightarrow (O_{\pi'} = O_\pi) \, W \, (I_{\pi'} \neq I_\pi)$$

$\Rightarrow$ we can omit the symmetric monitor instantiations

Transitivity - Example

For output-equality

$$\forall \pi. \forall \pi'. O_\pi = O_{\pi'}$$

we check whether the following formula is valid:

$$\forall \pi. \forall \pi'. \forall \pi''. (O_\pi = O_{\pi'}) \wedge (O_{\pi'} = O_{\pi''})$$
$$\rightarrow (O_{\pi'} = O_{\pi'''})$$

$\Rightarrow$ it is sufficient to store one reference trace

Reflexivity - Example

For observational determinism

$$\forall \pi. \forall \pi'. (O_\pi = O_{\pi'}) \, W \, (I_\pi \neq I_{\pi'})$$

we check whether the following formula is valid:

$$\forall \pi. (O_\pi = O_\pi) \, W \, (I_\pi \neq I_\pi)$$

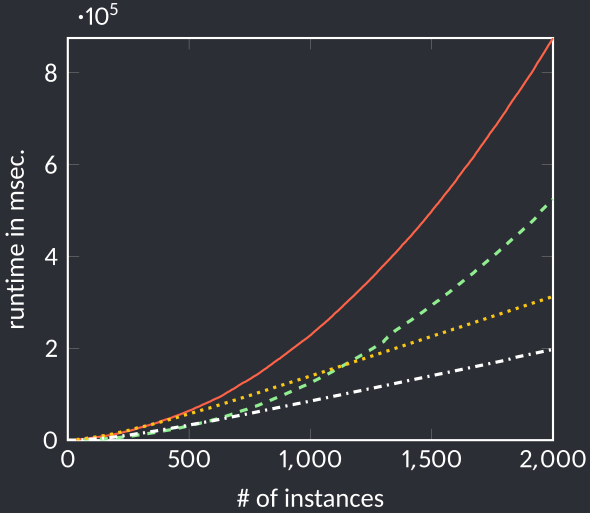
$\Rightarrow$ we can omit the reflexive monitor

Experiments

$$\forall \pi. \forall \pi'. (O_\pi = O_{\pi'}) \, W \, (I_\pi \neq I_{\pi'})$$

- naive monitoring approach
- trace analysis
- specification analysis
- combination of both

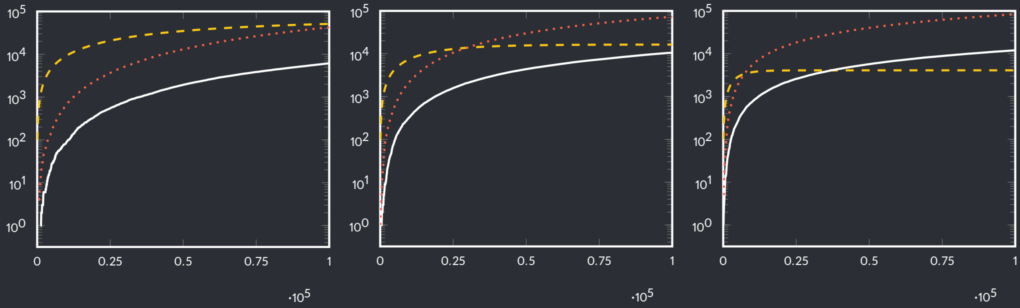
runtime on randomly generated traces



Experiments: Trace Analysis

$$\forall \pi. \forall \pi'. \square_{<n}(I_\pi = I_{\pi'}) \rightarrow \square_{<n+c}(O_\pi = O_{\pi'})$$

$n = 16$ $n = 14$ $n = 12$



- absolute numbers of violations
- number of instances stored
- number of instances pruned

10^5 randomly generated traces of length 100000

Experiments: Specification Analysis

		symm	trans	refl
ObsDet1	$\forall \pi. \forall \pi'.\ \Box(I_\pi = I_{\pi'}) \rightarrow \Box(O_\pi = O_{\pi'})$	✓	✗	✓
ObsDet2	$\forall \pi. \forall \pi'.\ (I_\pi = I_{\pi'}) \rightarrow \Box(O_\pi = O_{\pi'})$	✓	✗	✓
ObsDet3	$\forall \pi. \forall \pi'. (O_\pi = O'_\pi) \mathcal{W} (I_\pi \neq I'_\pi)$	✓	✗	✓
QuantNoninf	$\forall \pi_0 \ldots \forall \pi_c.\ \neg((\bigwedge_i I_{\pi_i} = I_{\pi_0}) \wedge \bigwedge_{i \neq j} O_{\pi_i} \neq O_{\pi_j})$	✓	✗	✓
EQ	$\forall \pi. \forall \pi'. \Box(a_\pi \leftrightarrow a_{\pi'})$	✓	✓	✓
ConfMan	$\forall \pi \forall \pi'. \big((\neg pc_\pi \wedge pc_{\pi'}) \rightarrow \bigcirc\Box(s_\pi \rightarrow \bigcirc v_{\pi'})\big)$ $\wedge \big((pc_\pi \wedge pc_{\pi'}) \rightarrow \bigcirc\Box(v_\pi \leftrightarrow v_{\pi'})\big)$	✗	✗	✗

- preprocessing can be done in a couple of seconds with EAHyper
- saves tremendous amount of time during the monitoring process

Summary

- monitoring hyperproperties in theory:

Monitor Template

Memory Explosion

- monitoring hyperproperties in practice:
  - Trace Analysis: exploits a dominance relation between traces
  - Specification Analysis: exploits symmetry, transitivity, and reflexivity in the specification

Bibliography

[Clarkson, Schneider, ’10] Clarkson, M. R., and F. B. Schneider. "Hyperproperties." Journal of Computer Security 18.6 (2010): 1157-1210.

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Pictures: http://russia-insider.com/sites/insider/files/20110226_bbd001_0.jpg

Monitorability

Theorem

Given a HyperLTL formula $\varphi = \forall \pi_1 \ldots \forall \pi_k.\psi$, where $\psi \not\equiv true$ is an LTL formula. φ is monitorable if, and only if, $\forall u \in \Sigma_{\mathcal{V}}^*.\exists v \in \Sigma_{\mathcal{V}}^*.uv \in bad(\mathcal{L}(\psi))$.

Theorem

Given an alternation-free HyperLTL formula φ. Deciding whether φ is monitorable is PSpace*-complete.*

Finite Trace Semantics

$$t[i,j] = \begin{cases} \epsilon & \text{if } i \geq |t| \\ t[i, min(j, |t|-1)], & \text{otherwise} \end{cases}$$

$\Pi_{fin} \models_T a_\pi$	if $a \in \Pi_{fin}(\pi)[0]$
$\Pi_{fin} \models_T \neg\varphi$	if $\Pi_{fin} \not\models_T \varphi$
$\Pi_{fin} \models_T \varphi \vee \psi$	if $\Pi_{fin} \models_T \varphi$ or $\Pi_{fin} \models_T \psi$
$\Pi_{fin} \models_T \bigcirc\varphi$	if $\Pi_{fin}[1,\ldots] \models_T \varphi$
$\Pi_{fin} \models_T \varphi\, U\, \psi$	if $\exists i \geq 0. \Pi_{fin}[i,\ldots] \models_T \psi \wedge \forall 0 \leq j < i. \Pi_{fin}[j,\ldots] \models_T \varphi$
$\Pi_{fin} \models_T \exists\pi.\varphi$	if there is some $t \in T$ such that $\Pi_{fin}[\pi \mapsto t] \models_T \varphi$

Alternation

An offline monitor for a $\forall^n\exists^m$HyperLTL and $\exists^m\forall^n$HyperLTL formula has to perform the checks

$$\bigwedge_{N\in T^n} \bigvee_{M\in T^m} \text{check if } \mathscr{M}_\varphi \text{ accepts } N \times M \text{ , and}$$

$$\bigvee_{M\in T^m} \bigwedge_{N\in T^n} \text{check if } \mathscr{M}_\varphi \text{ accepts } M \times N \text{ , respectively.}$$