Adventures in Monitorability

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joint work with:

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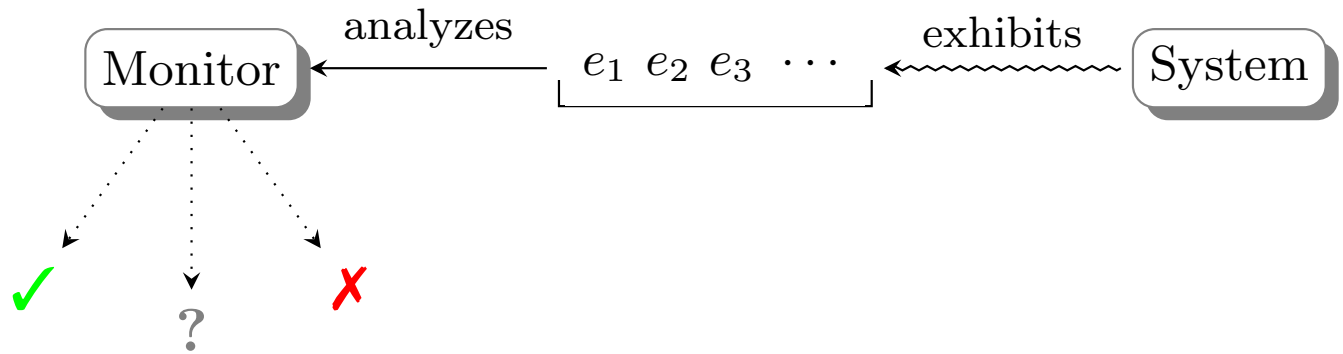
- Issues: systems become (even) larger and more complicated, unexpected environments, opaque components
- A post-deployment technique: Runtime Verification

Runtime Verification

- Runtime Verification uses monitors to detect at runtime whether a certain system satisfies/violates a specification.
- A monitor runs together with a process and it observes the events the process generates.
- When it detects a certain kind of behavior, it can reach a verdict (`yes`, `no`, or `end`).



Goals

Automatic monitor synthesis from specifications

Plausible monitorability guarantees for classes of properties

To determine the limits of monitorability

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A choice to make:

properties of
- processes
- infinite traces
- finite or infinite traces

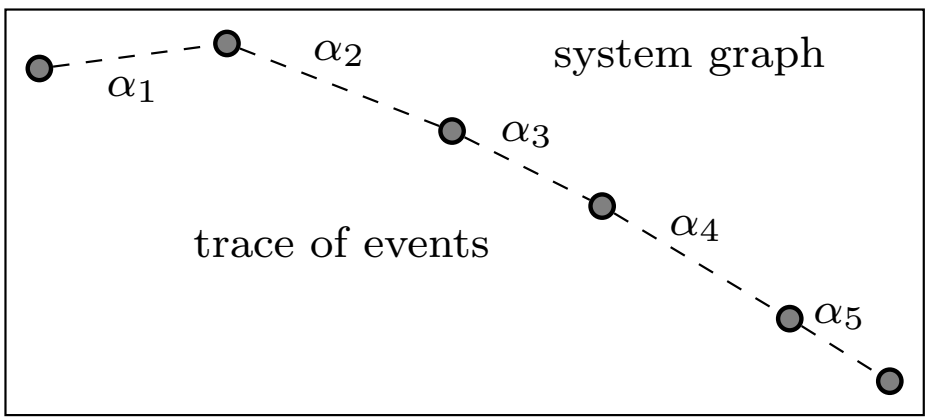
Two Kinds of Models – Two Kinds of Properties

Processes, Infinite Traces

$$\langle P, \text{Act}, \rightarrow \rangle$$

processes, actions, transitions

$$p \xrightarrow{\alpha_1} q \xrightarrow{\alpha_2} \cdots$$



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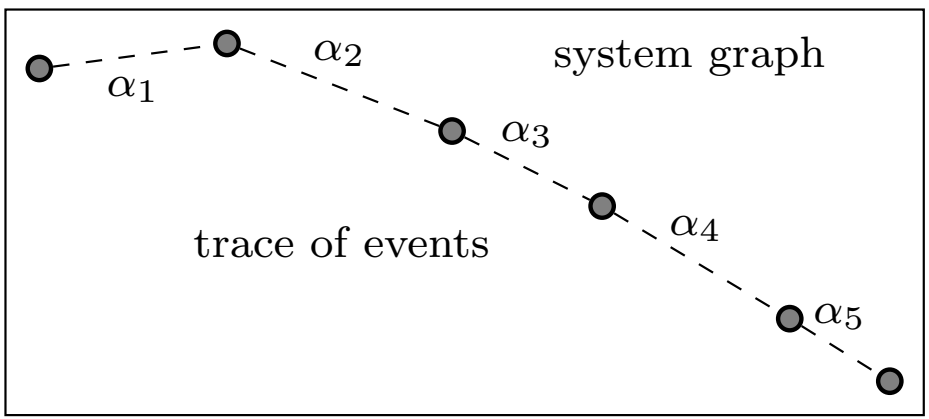

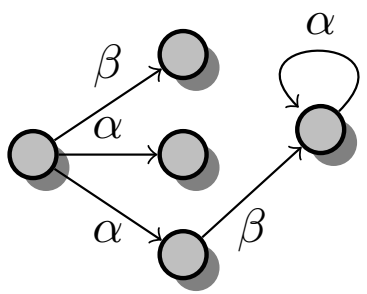

$$\alpha_1\alpha_2\alpha_3\cdots \in \textsc{Act}^\omega$$

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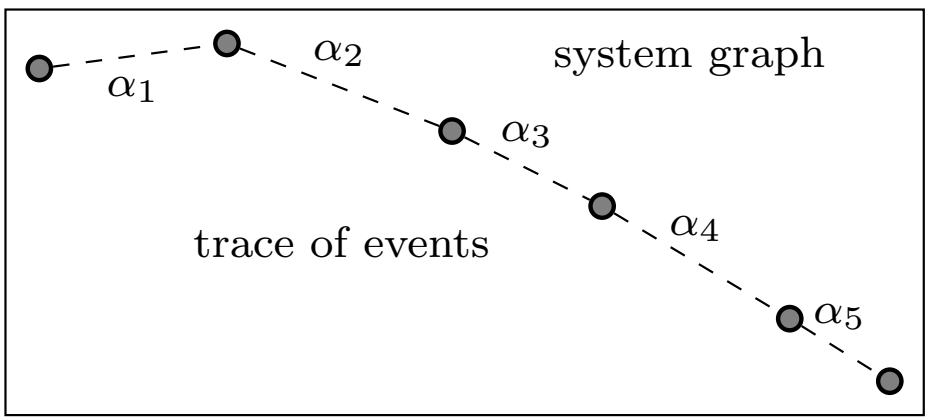

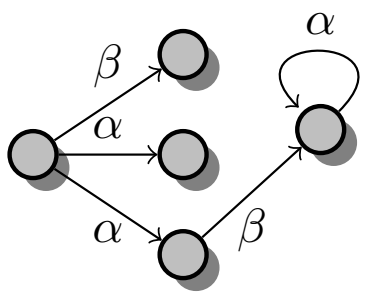

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Moral of the talk: The choice of model matters!

The Language

$$\varphi, \psi \in \mu\text{HML} ::= \texttt{tt} \mid \langle\alpha\rangle\varphi \mid \varphi \vee \psi \mid \min X.\varphi \mid X$$
$$\mid \texttt{ff} \mid [\alpha]\varphi \mid \varphi \wedge \psi \mid \max X.\varphi$$

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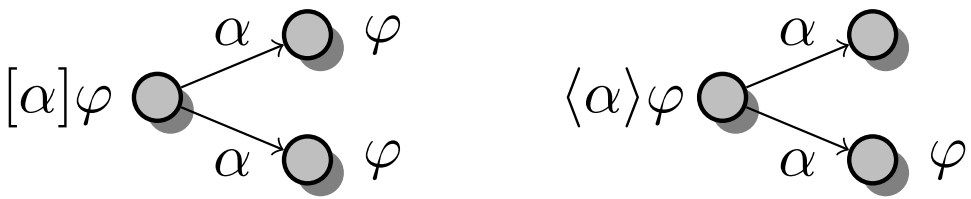
A branching-time language...



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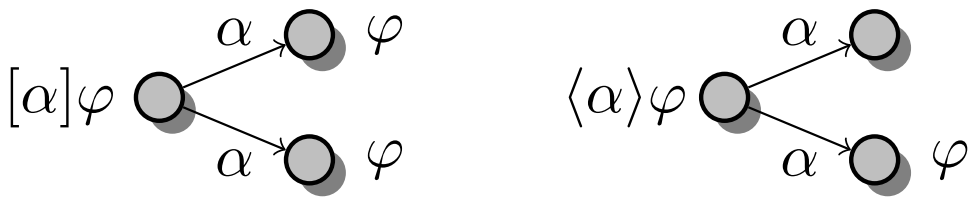

...or, possibly, a linear-time language...

$$s \models [\alpha]\varphi : \quad s = \alpha\ s' \implies s' \models \varphi$$

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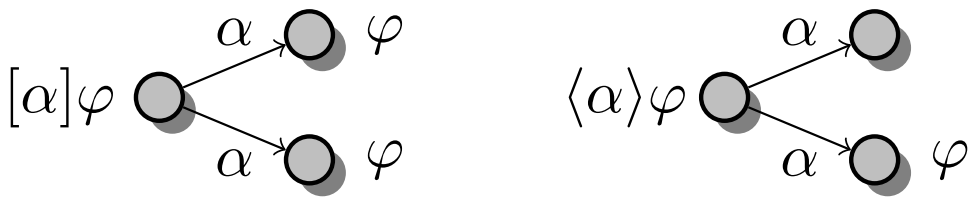

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...with recursion

$\min X.\varphi$ holds iff $\varphi[\min X.\varphi/X]$ does and is a lfp

$\max X.\varphi$ holds iff $\varphi[\max X.\varphi/X]$ does and is a gfp

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An *expressive* language:

can encode LTL, CTL, CTL*, BA,...

Shorthands from LTL on infinite traces:

$$\mathsf{X}\ \varphi := [\textsc{Act}]\varphi \qquad \text{(next step)}$$
$$\mathsf{F}\ \varphi := \min Y.(\varphi \vee \mathsf{X}\ Y) \qquad \text{(in the future)}$$
$$\mathsf{G}\ \varphi := \max Y.(\varphi \wedge \mathsf{X}\ Y) \qquad \text{(generaly)}$$
$$\varphi\ \mathsf{U}\ \psi := \min Y.(\psi \vee (\varphi \wedge \mathsf{X}\ Y)) \qquad \text{(until)}$$

Regular Monitors

Syntax:

$$m, n \in \textsc{Mon} ::= \texttt{end} \mid \texttt{no} \mid \alpha.m \mid m + n \mid \texttt{rec}\ x.m \mid x$$

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Monitor LTS (verdicts are irrevocable):

$$\textsc{Act}\ \frac{}{\alpha.m \xrightarrow{\alpha} m} \qquad \textsc{Rec}\ \frac{m[\texttt{rec}x.m/x] \xrightarrow{\alpha} n}{\texttt{rec}x.m \xrightarrow{\alpha} n} \qquad \textsc{Vrd}\ \frac{}{\texttt{no} \xrightarrow{\alpha} \texttt{no}}$$

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Instrumentation (follow the trace):

$$\textsc{iMon}\frac{p \xrightarrow{\alpha}_L q \quad m \xrightarrow{\alpha}_M n}{m \triangleleft p \xrightarrow{\alpha}_I n \triangleleft q} \qquad \textsc{iTer}\frac{p \xrightarrow{\alpha}_L q \quad m \overset{\alpha}{\not\longrightarrow}_M}{m \triangleleft p \xrightarrow{\alpha}_I \texttt{end} \triangleleft q}$$

Formulas and Rejection-Monitors

- Formulas specify process properties: $p \models \varphi$
- Monitors run along a process and read its trace:
  $$m \triangleleft p \xrightarrow{\alpha_1} n \triangleleft q \xrightarrow{\alpha_2} \cdots$$
- A monitor can reach three possible verdicts: `yes`, `no`, `end`
- m accepts p when $m \triangleleft p \xrightarrow{\alpha_1} \cdots \xrightarrow{\alpha_r} \texttt{yes} \triangleleft q$
  m rejects p when $m \triangleleft p \xrightarrow{\alpha_1} \cdots \xrightarrow{\alpha_r} \texttt{no} \triangleleft q$
  for some $\alpha_1 \cdots \alpha_r$ and q
- `end` is the inconclusive verdict.

Definition (Complete Monitorability)

m monitors completely for φ when

- m accepts exactly the processes that satisfy φ; and
- m rejects exactly the ones that do not satisfy φ.

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say m accepts p and rejects q

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Definition (Partial Monitorability)

- m is *sound* (s.) for φ if it only accepts (rejects) processes that satisfy (violate) φ;
- m is *satisfaction-complete* (s.c.) for φ when m accepts all the processes that satisfy φ; and
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Monitors for μHML (on processes)

FAI17, AAFI17

We can monitor for sHML, the safety fragment of μHML:

$$\varphi, \psi \in \text{sHML} ::= \texttt{tt} \mid \texttt{ff} \mid [\alpha]\varphi \mid \varphi \wedge \psi \mid \max X.\varphi \mid X.$$

Monitor Synthesis Function: $\varphi \mapsto m(\varphi)$ (follow the syntax).
Formula Synthesis Function: $m \mapsto f(m)$.

Theorem (Monitorability – Maximality)

$m(\varphi)$ monitors for φ and m monitors for $f(m)$.
The basic monitoring system monitors for sHML.

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Question: How about diamonds? $\langle\alpha\rangle\mathtt{tt}$

On Infinite Traces

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Parallel monitors: we introduce two parallel operators, $\otimes$ and $\oplus$

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Parallel Monitors and maxHML

The monitorable syntactic fragments of μHML are now larger:

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\varphi, \psi \in \text{minHML} ::= \ & \mathtt{tt} \mid \langle\alpha\rangle\varphi \mid \varphi \vee \psi \mid X \\
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\end{aligned}$$

$$\begin{aligned}
m(\langle\alpha\rangle\varphi) &= \alpha.m(\varphi) + \overline{\alpha}.\mathtt{no} & m(\varphi \wedge \psi) &= m(\varphi) \otimes m(\psi) \\
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Are parallel monitors a reasonable model?
infinite-state; more powerful than regular monitors(?)

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maxHML $\cap$ minHML appears to be nontrivial

Regularization

Parallel monitors are convenient, but not more powerful:

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$m(\varphi)$ is equivalent to a regular monitor of size $2^{O(|m(\varphi)|\cdot 2^{|m(\varphi)|})}$.

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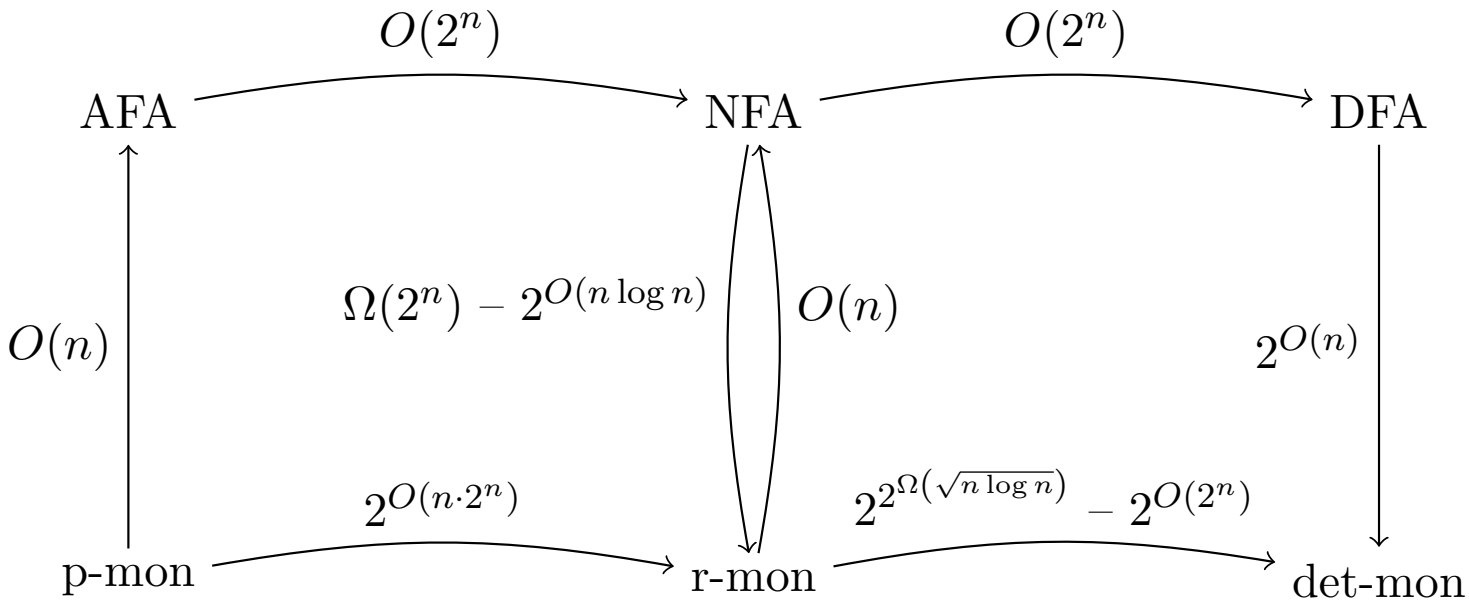

Surprise!

Complete monitorability *is* possible, after all

You cannot combine an accepting and a rejecting trace into one

$$m([\alpha][\beta]\mathtt{ff} \wedge [\beta][\alpha]\mathtt{ff}) \equiv \alpha.\beta.\mathtt{no} + \beta.\alpha.\mathtt{no} + \alpha.\alpha.\mathtt{yes} + \beta.\beta.\mathtt{yes}$$

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$$m([\alpha][\beta]\mathtt{ff} \wedge [\beta][\alpha]\mathtt{ff}) \equiv \alpha.\beta.\mathtt{no} + \beta.\alpha.\mathtt{no} + \alpha.\alpha.\mathtt{yes} + \beta.\beta.\mathtt{yes}$$

Theorem (Complete Monitorability)

For $\varphi \in HML$, $m(\varphi)$ monitors completely for φ over linear time.

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Theorem (Complete Monitorability)

For $\varphi \in HML$, $m(\varphi)$ monitors completely for φ over linear time.

Furthermore, all completely monitorable μHML trace-properties can be (constructively) written in HML — so, HML is (semantically) maximal.

Even Better: General Maximality of HML

All trace properties, irrespective of the monitoring system can be expressed in HML:

Theorem (General Maximality for HML)

Let m be a monitor from a monitoring system such that:

1. *verdicts are irrevocable: if m accepts/rejects a finite trace, then it accepts/rejects all its extensions, and*
2. *m accepts/rejects t iff, it accepts/rejects some finite prefix.*

For any property φ with a trace interpretation (not necessarily written in μHML), if m is sound and complete for φ then φ can be expressed in HML.

Proof sketch.

Every trace either satisfies φ or not, so m accepts or rejects. By König's Lemma, there is a finite set of finite traces that determine φ. Describe these in HML. □

Maximality for Partial Monitorability

and a collapse

Theorem (Partial Monitorability for Linear-Time)

For $\varphi \in$ maxHML (minHML), $m(\varphi)$ is sound and violation-(satisfaction-)complete for φ.

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Proof of maximality.

We can transform:

m to regular n

n to $f(n) \in \text{sHML} \subseteq \text{maxHML}$. □

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No: μHML properties are (ω-)regular and we can monitor with (say) PDAs.

How fast does your monitor return a verdict?

$\langle a \rangle [a][b]\mathtt{tt}$ $\qquad$ $b.\mathtt{no} + a.(b.\mathtt{yes} + a.(a.\mathtt{yes} + b.\mathtt{yes}))$ $\qquad$ $a\ a\ b\ a\ \cdots$

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Definition

A monitor m is *tight* when for every finite s, if m rejects all infinite extensions of s, then m rejects s.

We want to construct tight monitors.

Constructing Tight Monitors for HML

Slim formulas:

$$\varphi ::= \mathtt{tt} \mid \mathtt{ff} \mid \bigwedge_{\alpha \in B} [\alpha]\varphi_\alpha \mid \bigvee_{\alpha \in D} \langle\alpha\rangle\psi\alpha,$$

where $B, D \neq \emptyset$, $\varphi_\alpha \neq \mathtt{tt}$, $\psi_\alpha \neq \mathtt{ff}$, and no $\bigwedge_{\alpha \in \text{Act}} [\alpha]\mathtt{ff}$ or $\bigvee_{\alpha \in \text{Act}} \langle\alpha\rangle\mathtt{tt}$

(i.e. nothing is immediately true or false, except $\mathtt{tt}$ and $\mathtt{ff}$).

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The dieting process is based on rewrite rules based on simple equivalences: $[\mathrm{ACT}]\mathtt{ff} \Rrightarrow \mathtt{ff}$, $\langle\mathrm{ACT}\rangle\mathtt{tt} \Rrightarrow \mathtt{tt}$, $\langle\alpha\rangle\mathtt{ff} \Rrightarrow \mathtt{ff}$, $[\alpha]\varphi \wedge [\alpha]\psi \Rrightarrow [\alpha](\varphi \wedge \psi)$, $[\alpha]\varphi \vee [\beta]\psi \Rrightarrow \mathtt{tt}$, $\langle\alpha\rangle\varphi \wedge [\beta]\psi \Rrightarrow \langle\alpha\rangle\varphi$ ...

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Proposition

The result of the above process is tight.

The resulting monitor can be triple-exponentially larger than φ.

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Probably not: `no` is the tight monitor for φ iff φ is not satisfiable.

Proposition (Upper bound from Vardi, 1988)

maxHML-*satisfiability on infinite traces is* PSPACE-*complete (for* $|\text{Act}| > 1$*).*

Into the Finfinite: $\alpha_1\ \alpha_2\ \alpha_3\ \alpha_4 \cdots ?$

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maximally monitorable fragments:

$$\begin{array}{rcccccccc}
\varphi,\psi \in \textsc{unHML} ::= & \mathtt{tt} & | & \mathtt{ff} & | & [\alpha]\varphi & & \\
| & \varphi \vee \psi & | & \varphi \wedge \psi & | & \max X.\varphi & | & X, \\
\varphi,\psi \in \textsc{exHML} ::= & \mathtt{tt} & | & \mathtt{ff} & | & \langle\alpha\rangle\varphi & & \\
| & \varphi \vee \psi & | & \varphi \wedge \psi & | & \min X.\varphi & | & X.
\end{array}$$

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\end{array}$$

$\textsc{unHML} \equiv \textsc{sHML}$, $\textsc{exHML} \equiv \textsc{cHML}$ over finfinite traces

What we did

- Automatic monitor synthesis from l.t. maxHML, minHML
  - Either directly from maxHML or minHML, to construct a parallel monitor and then regularize, or from sHML or cHML, to directly give a regular monitor.
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  - Monitorable formulas are closed under $\wedge, \vee$ for l.t., but not for branching time.
- Moral: when you study the properties of monitorability, the choice of the model matters!

Future work

- More complexity bounds
- What *is* monitorability, after all? Relation to other concepts, the rest of the RV community?
- Relations to similar concepts: diagnosability, learning,...
- Distributed RV, fault tolerance, Epistemic Logic, evidence tracking.
- Real time
- ...

More Variations for the Interested

- Silence and obscuring:
  - Sometimes we abstract away from internal system behaviour using a *silent* action τ.
  - Often, a silent transition is almost-visible due to evaluating conditions, system noise, or by design...
  - A framework for grades of *obscuring* of silent actions and *reliable* monitorability [AAFI17]
- Monitoring with conditions [AAFI18]
- Sound/optimal monitorability [Leh]

The End

Time for questions

Thank you for your attention

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Short Bibliography for Further Reading

The TheoFoMon project page: `http://icetcs.ru.is/theofomon/`

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