Runtime Verification of Safety-Progress Properties

9^{th} International Workshop on Runtime Verification

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Verimag, Grenoble Universities

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"Classical" runtime validation method: monitoring

Runtime Verification [Havelund,Rosu]

- A lightweight verification technique "bridging the gap" between **testing** and **verification**
- **Checking** whether a run of the system under scrutiny satisfies a given correctness property

"Classical" runtime validation method: monitoring

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- A lightweight verification technique "bridging the gap" between **testing** and **verification**
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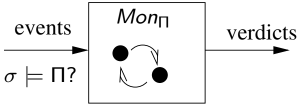
Instrument the underlying program to observe relevant events

A monitor acts as an **oracle** for the property (validation/violation)



Enforcement Monitoring: extension of monitoring

Gaining more confidence?

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- Prevent a misbehavior of the program?

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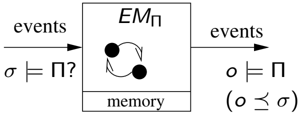

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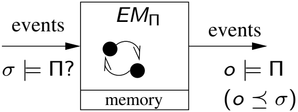

Underlying mechanism: enforcement monitor
$\hookrightarrow$ modifies the current execution sequence

Informal principle [Schneider, Ligatti and al.]

1. Output sequences are correct: soundness
2. Correct original execution sequences remain unchanged: transparency

Previous Mechanisms and enforceable properties

- Schneider and al.: security-automata and safety properties
- Ligatti and al.: edit-automata and renewal properties

Our proposal

Which properties those techniques can address ?

Characterization of some "classes" of properties

Based on the Safety-Progress classification [Manna,Pnueli]
$\hookrightarrow$ Unified framework with several views of properties (logical, automata,. . .)

Revisiting and extending existing results in this uniform framework

(Simple) Synthesis techniques of monitors

Outline

1. The Safety-Progress Classification of Properties [Manna,Pnueli]
2. Monitorable Properties
3. Enforceable properties
4. Synthesis of Monitors from Streett Automata
5. Conclusion and future works

Outline

1. The Safety-Progress Classification of Properties [Manna,Pnueli]
   - Overview
   - The automata view
2. Monitorable Properties
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Overview (1)

General classification of linear temporal properties

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Fine-grain definition of classes of properties

- basic classes: safety, guarantee, response, persistence
- compound classes: obligation, reactivity

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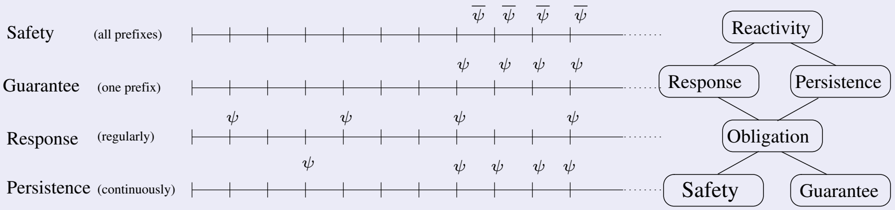
The intuitive/informal idea



Overview (2)

Characterization according to several views

- **automata**: Streett automata
- logical, language-theoretic, topological

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Customizing the SP classification for runtime verification

- Initially defined for infinite execution sequences
- Monitoring context
  - Processing incremental **finite** sequences
  - Verdict taken on finite sequences

Our properties: *r*-properties: (ϕ, φ)

- ϕ: the finitary property
- φ: the infinitary property

There should be a "link" between ϕ and φ

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Finite state automata: Streett automata

Definition of a deterministic Streett m-automaton

A tuple $(Q, q_{\text{init}}, \Sigma, \longrightarrow, \{(R_1, P_1), \ldots, (R_m, P_m)\})$

- Q is the set of automaton states ($q_{\text{init}} \in Q$ is the initial state),
- total function $\longrightarrow: Q \times \Sigma \rightarrow Q$ is the transition function,
- $\{(R_1, P_1), \ldots, (R_m, P_m)\}$ is the set of accepting pairs, $\forall i \leq n$,
  - $R_i \subseteq Q$ are the sets of recurrent states,
  - and $P_i \subseteq Q$ are the sets of persistent states.

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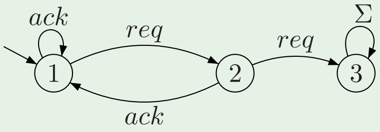
Example (Streett automata)



$R = \{1\}$

"Every request is acknowledged, and never two successive requests"

Acceptance criteria

Acceptance condition for **Infinite sequences**

For $\sigma \in \Sigma^\omega$, $\mathcal{A}$ accepts σ if
$\forall i \in [1, m], vinf(\sigma, \mathcal{A}) \cap R_i \neq \emptyset \vee vinf(\sigma, \mathcal{A}) \subseteq P_i$
where $vinf(\sigma, \mathcal{A})$: set of states visited infinitely often

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(This semantics is similar to the semantics of RV-LTL [Bauer and al.])

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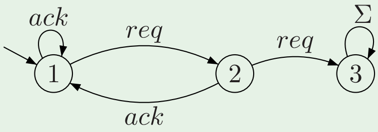

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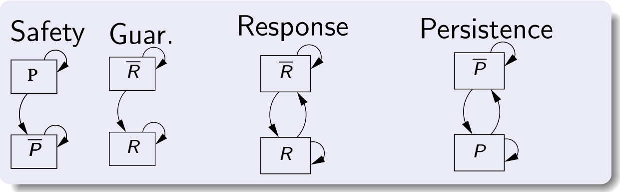
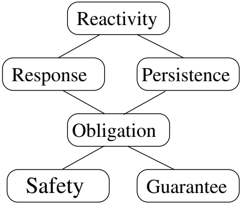
The automata view

Classification according to syntactic restrictions on automata

- **safety**: $R = \emptyset$ and no transition from $q \in \overline{P}$ to $q' \in P$.
- **guarantee**: $P = \emptyset$ and no transition from $q \in R$ to $q' \in \overline{R}$
- **response**: $P = \emptyset$
- **persistence**: $R = \emptyset$
- *m-obligation*: m-automaton
  - no transition from $q \in \overline{P_i}$ to $q' \in P_i$,
  - no transition from $q \in R_i$ to $q' \in \overline{R_i}$,
- *m-reactivity*: unrestricted m-automaton





Outline

1 The Safety-Progress Classification of Properties [Manna,Pnueli]

2 Monitorable Properties
- Classical definition of Monitorability
- Refinement of the notion of monitorability

3 Enforceable properties

4 Synthesis of Monitors from Streett Automata

5 Conclusion and future works

Classical definition of monitorability [Pnueli,Zaks]

"Determine verdict of infinite sequences with (finite) observations"

$\hookrightarrow$ evaluation depends on the satisfaction of the current sequence and its continuations

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Properties $\oplus$/$\ominus$-determined

Considering $\sigma \in \Sigma^*$, a r-property $\Pi = (\phi, \varphi)$ is said to be:

- $\ominus$-determined by σ, if $\neg\Pi(\sigma \cdot \mu)$ for all completions $\mu \in \Sigma^\infty$
  $\hookrightarrow$ verdict $\perp$
- $\oplus$-determined by σ, if $\Pi(\sigma \cdot \mu)$ for all completions $\mu \in \Sigma^\infty$
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Truth $\mathbb{B}$ domain determines the class of monitorable properties
$\hookrightarrow$ $MP(\mathbb{B})$: the set of monitorable properties with $\mathbb{B}$

Characterization of monitorability

Truth-domain of cardinality 3: $Obligation \subset MP(\{?, \bot, \top\})$

- Safety properties are monitorable
- Guarantee properties are monitorable
- Union and intersection of monitorable properties is monitorable

(Exact characterization on a Streett automaton)

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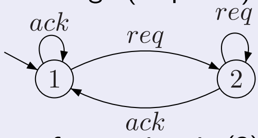
Non-monitorable properties

- (some) Response, Persistence, and Reactivity properties
- Impossible to detect $\top$ or $\perp$
- Example: request/acknowledge (response) properties [Bauer and al.]

in LTL: $\Box(r \Rightarrow \Diamond a)$



$\hookrightarrow$ the output sequence of a monitor is $(?)^*$

Refinement of the notion of monitorability

Following [Bauer and al.] and the motivations of RV-LTL:

- Trying to answer "What happens if the program execution stops here"
- Distinguish prefixes which evaluated previously to ?

Considering the truth-domain $\mathbb{B}_4 = \{\bot, \bot^p, \top^p, \top\}$:

- $\bot_p$: presumably false
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Definition (Refinement of monitorability)

- $[\![\Pi]\!](\sigma) = \top$ if $\Pi(\sigma) \wedge \forall \mu \in \Sigma^\infty \cdot \Pi(\sigma \cdot \mu)$
- $[\![\Pi]\!](\sigma) = \top_p$ if $\Pi(\sigma) \wedge \exists \mu \in \Sigma^\infty \cdot \neg\Pi(\sigma \cdot \mu)$
- $[\![\Pi]\!](\sigma) = \bot_p$ if $\neg\Pi(\sigma) \wedge \exists \mu \in \Sigma^\infty \cdot \Pi(\sigma \cdot \mu)$
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Theorem ($MP(\mathbb{B}_4) = Reactivity(\Sigma)$)

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Enforcement, soundness, and transparency

Soundness and transparency:

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Consequence: input sequence σ should be modified *in a minimal way*:

- $\sigma \models \Pi \Rightarrow$ it should remain unchanged (up to an equivalence relation),
- $\sigma \not\models \Pi \Rightarrow$ its *longest prefix* satisfying Π should be issued.

Expected for both finite and infinite execution sequences

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Consequence: enforceability criterion for $\Pi = (\phi, \varphi)$

Each infinite incorrect sequence has a *longest* correct prefix,
$\hookrightarrow$ *i.e.* a finite number of correct prefixes.

Enforcement Criterion and response properties

Definition (Enforcement criterion)

A r-property $\Pi = (\phi, \varphi)$ is said to be enforceable iff

$$\forall \sigma \in \Sigma^\omega, \left(\neg\varphi(\sigma) \Rightarrow (\exists \sigma' \in \Sigma^*, \sigma' \prec \sigma, \forall \sigma'' \in \Sigma^* \cdot \sigma' \prec \sigma'' \Rightarrow \neg\phi(\sigma''))\right)$$

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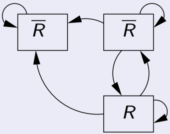
Theorem (Response are enforceable: $Response(\Sigma) \subseteq EP$)

Sketch of proof

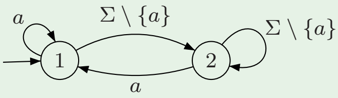
- Consider $\sigma_{bad} \in \Sigma^\omega$
- $\neg\varphi(\sigma) \Rightarrow vinf(\sigma_{bad}) \cap R = \emptyset$
- run "stays" in $\overline{R}$ from a certain point



Straightforward consequence: safety, guarantee and obligation r-properties are enforceable.

Pure persistence properties are not enforceable

Example



$\Pi = (\Sigma^* \cdot a^+, \Sigma^* \cdot a^\omega)$: "it will be eventually true that a always occur"
$vinf(\sigma, \mathcal{A}_\Pi) \subseteq P$ and $P = \{1\}$

- $\sigma_{bad} = (ab)^\omega$
- $\neg\Pi(\sigma_{bad})$ since $vinf(\sigma_{bad}, \mathcal{A}_\Pi) = \{1, 2\}$
- but $\forall i \in \mathbb{N}, \Pi\big((ab)^i \cdot a\big)$ since $P = \{1\}$

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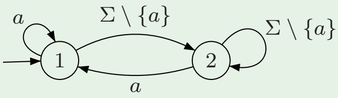

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In other words:

- decide from a certain point that the underlying program will always produce the event a
- decision cannot be taken without reading and memorizing first the entire execution sequence.

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4. Synthesis of Monitors from Streett Automata
   - Preliminaries on Streett Automata
   - Runtime Verification and Enforcement Monitors
5. Conclusion and future works

Streett m-automaton $\mathcal{A} = (Q^{\mathcal{A}}, {q_{\mathrm{init}}}^{\mathcal{A}}, \longrightarrow_{\mathcal{A}}, \{(R_1, P_1), \ldots, (R_m, P_m)\})$.

General Idea: (syntactic) characterization of the states according to the verdict to be produced

Definition ($\mathbb{P}^{\mathcal{A}}$ (good, presumably good, presumably bad, bad states))

- $Good^{\mathcal{A}} = \{q \in Q^{\mathcal{A}} \cap \bigcap_{i=1}^{m}(R_i \cup P_i) \mid Reach_{\mathcal{A}}(q) \subseteq \bigcap_{i=1}^{m}(R_i \cup P_i)\}$
- $Good_p^{\mathcal{A}} = \{q \in Q^{\mathcal{A}} \cap \bigcap_{i=1}^{m}(R_i \cup P_i) \mid Reach_{\mathcal{A}}(q) \not\subseteq \bigcap_{i=1}^{m}(R_i \cup P_i)\}$
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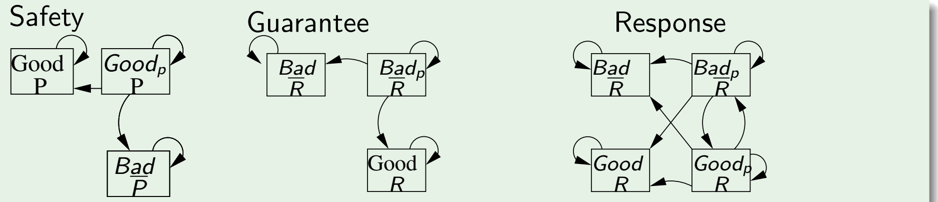
Note that $Q^{\mathcal{A}} = Good^{\mathcal{A}} \cup Good_p^{\mathcal{A}} \cup Bad_p^{\mathcal{A}} \cup Bad^{\mathcal{A}}$.



Runtime verification and enforcement Monitors

Definition (Monitor)

$\mathcal{A}$ is a 5-tuple $(Q^{\mathcal{A}}, q_{\text{init}}{}^{\mathcal{A}}, \longrightarrow_{\mathcal{A}}, X^{\mathcal{A}}, \Gamma^{\mathcal{A}})$ (defined relatively to Σ)

- a (classical) FSM
- The set of values $X^{\mathcal{A}}$ depends on the purpose of the monitor (verification or enforcement)
- $\Gamma^{\mathcal{A}} : Q^{\mathcal{A}} \rightarrow X^{\mathcal{A}}$, output function, producing values in $X^{\mathcal{A}}$ from states.

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Runtime Verification and Enforcement Monitors

Using $\mathbb{P}$ to define the output function $\Gamma^{\mathcal{A}}$ (depends on the current state)

- For runtime verification: $X^{\mathcal{A}} = \mathbb{B}_4$
- For runtime enforcement:
  - $X^{\mathcal{A}} = \{halt, store, dump, off\}$
  - using an internal memory: a FIFO queue

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Conclusion

Monitorability and enforceability at runtime using a general framework

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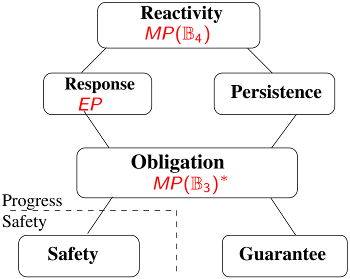
Monitorability and enforceability at runtime using a general framework

- Characterization of monitorable and enforceable properties in a unified way.
- Encompassing previous definitions of monitorability
(previous definitions can be derived by reducing the truth-domain $\mathbb{B}_4$)



Synthesis procedures to generate runtime and enforcement monitors

Future works

The testing perspective:

- Differences:
    - A monitor (passively) observes the execution of the program
    - notion of *controlable* event is introduced
- Characterize the set of testable properties in a similar fashion
  $\hookrightarrow$ deal with a reduced observability on the system under scrutiny

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Space of properties for which others RV-like techniques can be applied (*e.g.* runtime reflection)

Further study the **practical feasibility** of the approach

- data dependency between events
- Memory limitation for the EM
- Influence on the enforcement ability: how the set of enforceable properties is impacted?