Technical Talk on Runtime Verification

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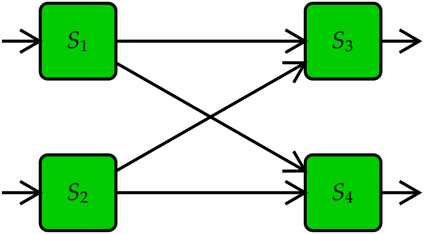
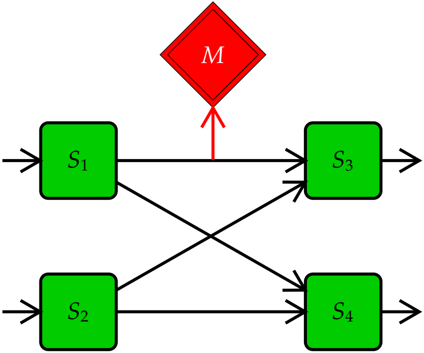
Runtime Verification (RV)

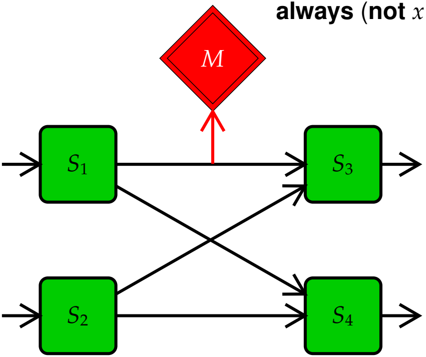


Runtime Verification (RV)



Runtime Verification (RV)

always (**not** $x > 0$ **implies next** $x > 0$)



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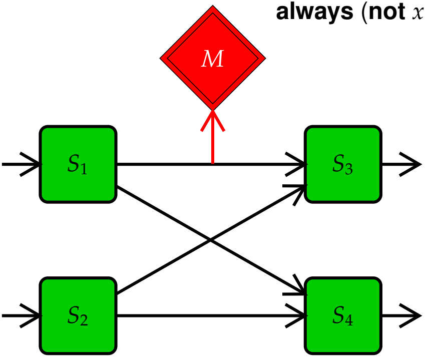

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Characterisation

- Verifies (partially) correctness properties based on actual executions

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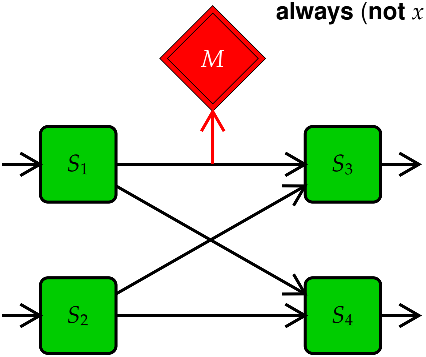

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- Verifies (partially) correctness properties based on actual executions
- Simple verification technique

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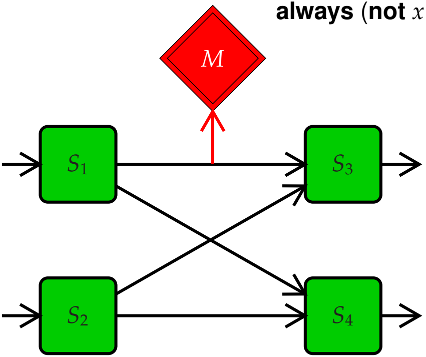

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- Simple verification technique
- Complementing

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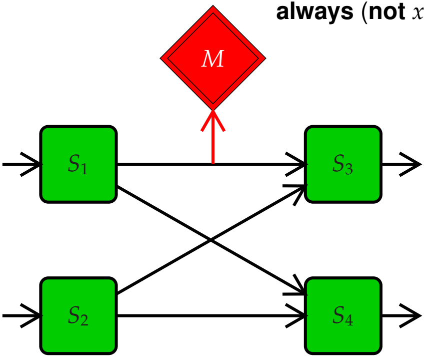

Characterisation

- Verifies (partially) correctness properties based on actual executions
- Simple verification technique
- Complementing
  - Model Checking

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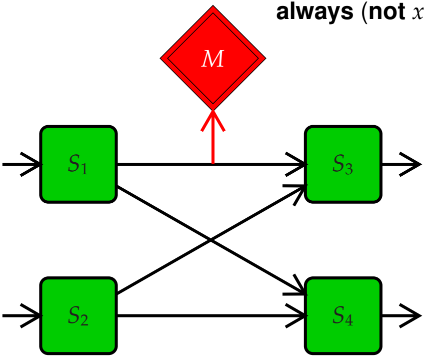

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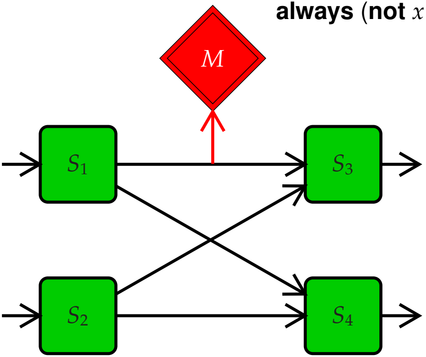

Characterisation

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  - Model Checking
  - Testing
- Formal: $w \in \mathcal{L}(\varphi)$

Model Checking

- Specification of System

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  - as formula φ of linear-time temporal logic (LTL)

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  - as transition system S with runs $\mathcal{L}(S)$

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- Model Checking Problem:
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  - $\mathcal{L}(S) \subseteq \mathcal{L}(\varphi)$

Model Checking versus RV

- Model Checking: infinite words

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Model Checking versus RV

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- Model Checking: White-Box-Systems
- Runtime Verification: also Black-Box-Systems

Testing

Testing: Input/Output Sequence

- incomplete verification technique

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- test oracle: monitor

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Testing: with Oracle

- test case: finite sequence of input actions
- test oracle: monitor
- test execution: send test cases, let oracle report violations
- similar to runtime verification

Testing versus RV

- Test oracle manual

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- RV monitor from high-level specification (LTL)

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- Testing:

  How to find good test suites?

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- RV monitor from high-level specification (LTL)
- Testing:

  How to find good test suites?
- Runtime Verification:

  How to generate good monitors?

Outline

- Runtime Verification
- Runtime Verification for LTL
  - LTL over Finite, Completed Words
  - LTL over Finite, Non-Completed Words: Impartiality
  - LTL over Non-Completed Words: Anticipation
  - LTL over Infinite Words: With Anticipation
  - Generalisations: LTL with modulo Constraints
  - Monitorable Properties
  - LTL with a Predictive Semantics
  - LTL wrap-up
- Extensions
- Monitoring Systems/Logging
- Steering
- Diagnosis
  - Ideas
  - RV and Diagnosis
- Conclusion

Presentation outline

Runtime Verification

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Runtime Verification

Definition (Runtime Verification)

Runtime verification is the discipline of computer science that deals with the study, development, and application of those verification techniques that allow checking whether a *run* of a system under scrutiny (SUS) satisfies or violates a given correctness property.

Its distinguishing research effort lies in *synthesizing monitors from high level specifications.*

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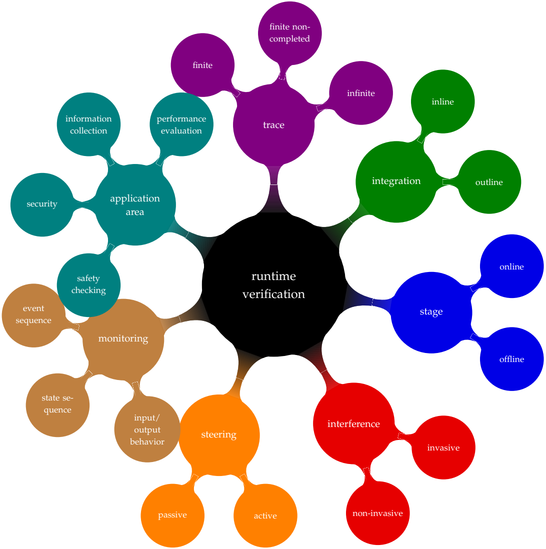
Definition (Monitor)

A monitor is a device that reads a finite trace and yields a certain verdict.

A verdict is typically a truth value from some truth domain.

Taxonomy


runtime verification
trace
finite
finite non-completed
infinite
integration
inline
outline
stage
online
offline
interference
invasive
non-invasive
steering
passive
active
monitoring
event sequence
state sequence
input/ output behavior
application area
information collection
performance evaluation
security
safety checking

Presentation outline

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Runtime Verification for LTL

Observing executions/runs

Runtime Verification for LTL

Observing executions/runs

Idea

Specify correctness properties in LTL

Runtime Verification for LTL

Observing executions/runs

Idea

Specify correctness properties in LTL

Commercial

Specify correctness properties in Regular LTL

Runtime Verification for LTL

Definition (Syntax of LTL formulae)

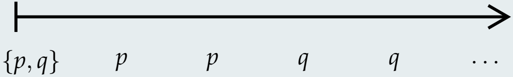
Let p be an atomic proposition from a finite set of atomic propositions AP. The set of LTL formulae, denoted with LTL, is inductively defined by the following grammar:

$$\begin{array}{rcl} \varphi & ::= & \mathit{true} \mid p \mid \varphi \vee \varphi \mid \varphi\, U\, \varphi \mid X\varphi \mid \\ & & \mathit{false} \mid \neg p \mid \varphi \wedge \varphi \mid \varphi\, R\, \varphi \mid \bar{X}\varphi \mid \\ & & \neg\varphi \end{array}$$

Linear-time Temporal Logic (LTL)

Semantics

over $w \in (2^{AP})^\omega = \Sigma^\omega$



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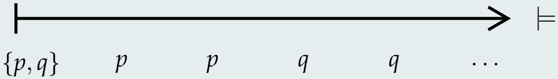

$\models$

$\{p, q\}$ p p q q $\dots$

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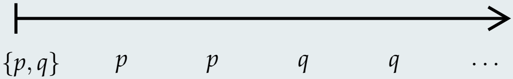

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p

$\neg p$

pUq

$X(pUq)$

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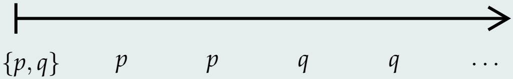

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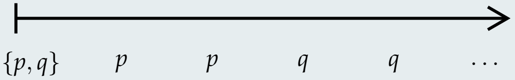

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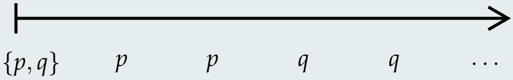

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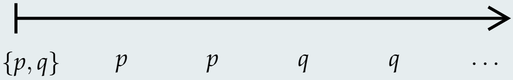

$\{p, q\}$ $\quad p \quad p \quad q \quad q \quad \cdots$

$\models$

p	✓
$\neg p$	✗
pUq	✓
$X(pUq)$	✓

Abbreviation

$F\varphi \equiv trueU\varphi \qquad G\varphi \equiv \neg F \neg \varphi$

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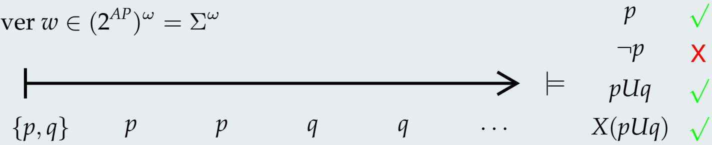

$\{p,q\}$ p p q q $\dots$ $\models$

p ✓

$\neg p$ ✗

pUq ✓

$X(pUq)$ ✓

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Example

$G\neg(critic_1 \wedge critic_2), G(\neg alive \rightarrow Xalive)$

LTL on infinite words

Definition (LTL semantics (traditional))

Semantics of LTL formulae over an infinite word $w = a_0 a_1 \ldots \in \Sigma^\omega$, where $w^i = a_i a_{i+1} \ldots$

$$
\begin{array}{lll}
w \models true & & \\
w \models p & \text{if} & p \in a_0 \\
w \models \neg p & \text{if} & p \notin a_0 \\
w \models \neg\varphi & \text{if} & \text{not } w \models \varphi \\
w \models \varphi \vee \psi & \text{if} & w \models \varphi \text{ or } w \models \psi \\
w \models \varphi \wedge \psi & \text{if} & w \models \varphi \text{ and } w \models \psi \\
w \models X\varphi & \text{if} & w^1 \models \varphi \\
w \models \bar{X}\varphi & \text{if} & w^1 \models \varphi \\
w \models \varphi \; U \; \psi & \text{if} & \text{there is } k \text{ with } 0 \leq k < |w| \text{: } w^k \models \psi \\
 & & \text{and for all } l \text{ with } 0 \leq l < k \; w^l \models \varphi \\
w \models \varphi \; R \; \psi & \text{if} & \text{for all } k \text{ with } 0 \leq k < |w| \text{: (} w^k \models \psi \\
 & & \text{or there is } l \text{ with } 0 \leq l < k \; w^l \models \varphi)
\end{array}
$$

LTL for the working engineer??

Simple??

“LTL is for theoreticians—but for practitioners?”

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Simple??

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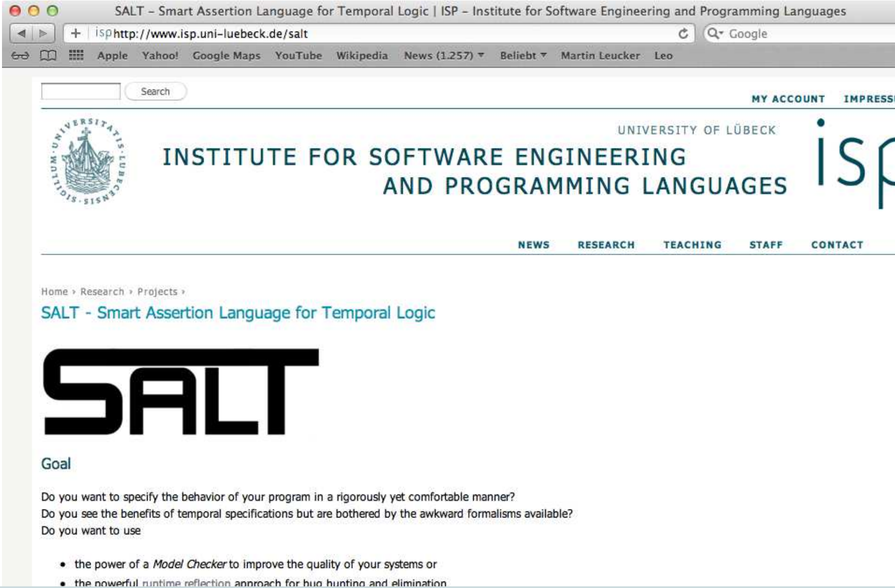
SALT

Structured Assertion Language for Temporal Logic

“Syntactic Sugar for LTL” [Bauer, L., Streit@ICFEM’06]

SALT – `http://www.isp.uni-luebeck.de/salt`


SALT – Smart Assertion Language for Temporal Logic | ISP – Institute for Software Engineering and Programming Languages
isp http://www.isp.uni-luebeck.de/salt
Google
Apple
Yahoo!
Google Maps
YouTube
Wikipedia
News (1.257)
Beliebt
Martin Leucker
Leo
Search
MY ACCOUNT
IMPRESS
UNIVERSITY OF LÜBECK
INSTITUTE FOR SOFTWARE ENGINEERING
AND PROGRAMMING LANGUAGES
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SALT

SALT - Smart Assertion Language for Temporal Logic

Goal

Do you want to specify the behavior of your program in a rigorously yet comfortable manner?
Do you see the benefits of temporal specifications but are bothered by the awkward formalisms available?
Do you want to use

- the power of a *Model Checker* to improve the quality of your systems or
- the powerful runtime reflection approach for bug hunting and elimination

Runtime Verification for LTL

Idea

Specify correctness properties in LTL

Definition (Syntax of LTL formulae)

Let p be an atomic proposition from a finite set of atomic propositions AP. The set of LTL formulae, denoted with LTL, is inductively defined by the following grammar:

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 & & \neg\varphi
\end{array}
$$

Truth Domains

Lattice

- A lattice is a partially ordered set $(\mathcal{L}, \sqsubseteq)$ where for each $x, y \in \mathcal{L}$, there exists
  1. a unique greatest lower bound (glb), which is called the meet of x and y, and is denoted with $x \sqcap y$, and
  2. a unique least upper bound (lub), which is called the join of x and y, and is denoted with $x \sqcup y$.
- A lattice is called finite iff $\mathcal{L}$ is finite.
- Every finite lattice has a well-defined unique least element, called bottom, denoted with $\bot$,
- and analogously a greatest element, called top, denoted with $\top$.

Truth Domains (cont.)

Lattice (cont.)

- A lattice is distributive, iff $x \sqcap (y \sqcup z) = (x \sqcap y) \sqcup (x \sqcap z)$, and, dually, $x \sqcup (y \sqcap z) = (x \sqcup y) \sqcap (x \sqcup z)$.
- In a de Morgan lattice, every element x has a unique dual element $\overline{x}$, such that $\overline{\overline{x}} = x$ and $x \sqsubseteq y$ implies $\overline{y} \sqsubseteq \overline{x}$.

Definition (Truth domain)

We call $\mathcal{L}$ a truth domain, if it is a finite distributive de Morgan lattice.

LTL's semantics using truth domains

Definition (LTL semantics (common part))

Semantics of LTL formulae over a finite or infinite word $w = a_0 a_1 \ldots \in \Sigma^\infty$

Boolean constants

$$\begin{aligned} [w \models \mathit{true}]_{\mathfrak{L}} &= \top \\ [w \models \mathit{false}]_{\mathfrak{L}} &= \bot \end{aligned}$$

Boolean combinations

$$\begin{aligned} [w \models \neg\varphi]_{\mathfrak{L}} &= \overline{[w \models \varphi]_{\mathfrak{L}}} \\ [w \models \varphi \vee \psi]_{\mathfrak{L}} &= [w \models \varphi]_{\mathfrak{L}} \sqcup [w \models \psi]_{\mathfrak{L}} \\ [w \models \varphi \wedge \psi]_{\mathfrak{L}} &= [w \models \varphi]_{\mathfrak{L}} \sqcap [w \models \psi]_{\mathfrak{L}} \end{aligned}$$

atomic propositions

$$[w \models p]_{\mathfrak{L}} = \begin{cases} \top & \text{if } p \in a_0 \\ \bot & \text{if } p \notin a_0 \end{cases} \qquad [w \models \neg p]_{\mathfrak{L}} = \begin{cases} \top & \text{if } p \notin a_0 \\ \bot & \text{if } p \in a_0 \end{cases}$$

next X/weak next X TBD

until/release

$$\begin{aligned} [w \models \varphi\ U\ \psi]_{\mathfrak{L}} &= \begin{cases} \top & \text{there is a } k,\ 0 \leq k < |w| : [w^k \models \psi]_{\mathfrak{L}} = \top \text{ and} \\ & \text{for all } l \text{ with } 0 \leq l < k : [w^l \models \varphi] = \top \\ \mathit{TBD} & \text{else} \end{cases} \\ \varphi\ R\ \psi &\equiv \neg(\neg\varphi\ U\ \neg\psi) \end{aligned}$$

Outline

- Runtime Verification
- Runtime Verification for LTL
  - LTL over Finite, Completed Words
  - LTL over Finite, Non-Completed Words: Impartiality
  - LTL over Non-Completed Words: Anticipation
  - LTL over Infinite Words: With Anticipation
  - Generalisations: LTL with modulo Constraints
  - Monitorable Properties
  - LTL with a Predictive Semantics
  - LTL wrap-up
- Extensions
- Monitoring Systems/Logging
- Steering
- Diagnosis
  - Ideas
  - RV and Diagnosis
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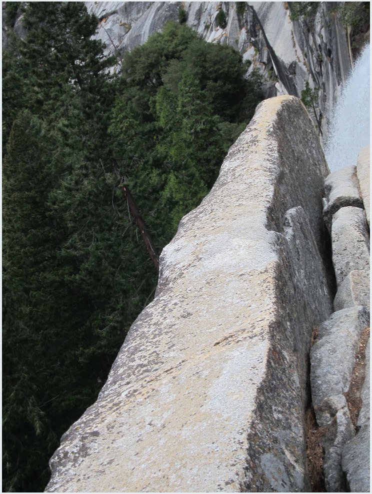
LTL on finite words

Application area: Specify properties of finite word



LTL on finite words

Definition (FLTL)

Semantics of FLTL formulae over a word $u = a_0 \dots a_{n-1} \in \Sigma^*$

next

$$[u \models X\varphi]_F \quad = \quad \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \bot & \text{otherwise} \end{cases}$$

weak next

$$[u \models \bar{X}\varphi]_F \quad = \quad \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \top & \text{otherwise} \end{cases}$$

Monitoring LTL on finite words

(Bad) Idea

just compute semantics. . .

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LTL on finite, but not completed words

Application area: Specify properties of finite but expanding word

LTL on finite, but not completed words

Be Impartial!

- go for a final verdict ($\top$ or $\bot$) only if you really know

LTL on finite, but not completed words

Be Impartial!

- go for a final verdict ($\top$ or $\bot$) only if you really know
- be a man: stick to your word

LTL on finite, but not complete words

Impartiality implies multiple values

Every two-valued logic is not impartial.

Definition (FLTL)

Semantics of FLTL formulae over a word $u = a_0 \dots a_{n-1} \in \Sigma^*$

next

$$[u \models X\varphi]_F = \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \perp^p & \text{otherwise} \end{cases}$$

weak next

$$[u \models \bar{X}\varphi]_F = \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \top^p & \text{otherwise} \end{cases}$$

Monitoring LTL on finite but expanding words

Left-to-right!

Monitoring LTL on finite but expanding words

Rewriting

Idea: Use rewriting of formula

Evaluating FLTL4 for each subsequent letter

- evaluate atomic propositions
- evaluate next-formulas
- that's it thanks to

$$\varphi\ U\ \psi \equiv \psi \vee (\varphi \wedge X\varphi\ U\ \psi)$$

  and

$$\varphi\ R\ \psi \equiv \psi \wedge (\varphi \vee \bar{X}\varphi\ R\ \psi)$$

- and remember what to evaluate for the next letter

Evaluating FLTL4 for each subsequent letter

Pseudo Code

```
evalFLTL4 $true$      a = ($\top$,$\top$)
evalFLTL4 $false$     a = ($\bot$,$\bot$)
evalFLTL4 p           a = ((p in a),(p in a))
evalFLTL4 $\neg\varphi$         a = let (valPhi,phiRew) = evalFLTL4 $\varphi$ a
                          in ($\overline{\texttt{valPhi}}$,¬phiRew)
evalFLTL4 $\varphi \vee \psi$   a = let
                            (valPhi,phiRew) = evalFLTL4 $\varphi$ a
                            (valPsi,psiRew) = evalFLTL4 $\psi$ a
                          in (valPhi $\sqcup$ valPsi,phiRew $\vee$ psiRew)
evalFLTL4 $\varphi \wedge \psi$   a = let
                            (valPhi,phiRew) = evalFLTL4 $\varphi$ a
                            (valPsi,psiRew) = evalFLTL4 $\psi$ a
                          in (valPhi $\sqcap$ valPsi,phiRew $\wedge$ psiRew)
evalFLTL4 $\varphi\, U\, \psi$   a = evalFLTL4 $\psi \vee (\varphi \wedge X(\varphi\, U\, \psi))$ a
evalFLTL4 $\varphi\, R\, \psi$   a = evalFLTL4 $\psi \wedge (\varphi \vee \bar{X}(\varphi\, R\, \psi))$ a
evalFLTL4 $X\varphi$        a = ($\bot^p$,$\varphi$)
evalFLTL4 $\bar{X}\varphi$        a = ($\top^p$,$\varphi$)
```

Monitoring LTL on finite but expanding words

Automata-theoretic approach

- Synthesize automaton
- Monitoring = stepping through automaton

Rewriting vs. automata

Rewriting function defines transition function

```
evalFLTL4 $true$       a = ($\top$,$\top$)
evalFLTL4 $false$      a = ($\bot$,$\bot$)
evalFLTL4 p            a = ((p in a),(p in a))
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```

Automata-theoretic approach

The roadmap

- alternating Mealy machines

Automata-theoretic approach

The roadmap

- alternating Mealy machines
- Moore machines

Automata-theoretic approach

The roadmap

- alternating Mealy machines
- Moore machines
- alternating machines

Automata-theoretic approach

The roadmap

- alternating Mealy machines
- Moore machines
- alternating machines
- non-deterministic machines

Automata-theoretic approach

The roadmap

- alternating Mealy machines
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Automata-theoretic approach

The roadmap

- alternating Mealy machines
- Moore machines
- alternating machines
- non-deterministic machines
- deterministic machines
- state sequence for an input word

Supporting alternating finite-state machines

Definition (Alternating Mealy Machine)

A alternating Mealy machine is a tupel $\mathcal{M} = (Q, \Sigma, \Gamma, q_0, \delta)$ where

- Q is a finite set of states,
- Σ is the input alphabet,
- Γ is a finite, distributive lattice, the output lattice,
- $q_0 \in Q$ is the initial state and
- $\delta : Q \times \Sigma \to B^+(\Gamma \times Q)$ is the transition function

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Convention

Understand $\delta : Q \times \Sigma \to B^+(\Gamma \times Q)$ as a function $\delta : Q \times \Sigma \to \Gamma \times B^+(Q)$

Supporting alternating finite-state machines

Definition (Run of an Alternating Mealy Machine)

A run of an alternating Mealy machine $\mathcal{M} = (Q, \Sigma, \Gamma, q_0, \delta)$ on a finite word $u = a_0 \dots a_{n-1} \in \Sigma^+$ is a sequence $t_0 \overset{(a_0,b_0)}{\to} t_1 \overset{(a_1,b_1)}{\to} \dots t_{n-1} \overset{(a_{n-1},b_{n-1})}{\to} t_n$ such that

- $t_0 = q_0$ and
- $(t_i, b_{i-1}) = \hat{\delta}(t_{i-1}, a_{i-1})$

where $\hat{\delta}$ is inductively defined as follows

- $\hat{\delta}(q, a) = \delta(q, a)$,
- $\hat{\delta}(q \vee q', a) = (\hat{\delta}(q, a)|_1 \sqcup \hat{\delta}(q', a)|_1, \hat{\delta}(q, a)|_2 \vee \hat{\delta}(q', a)|_2)$, and
- $\hat{\delta}(q \wedge q', a) = (\hat{\delta}(q, a)|_1 \sqcap \hat{\delta}(q', a)|_1, \hat{\delta}(q, a)|_2 \wedge \hat{\delta}(q', a)|_2)$

The output of the run is b_{n-1}.

Transition function of an alternating Mealy machine

Transition function $\delta_4^a : Q \times \Sigma \to B^+(\Gamma \times Q)$

$$
\begin{array}{lcl}
\delta_4^a(\mathit{true}, a) & = & (\top, \mathit{true}) \\
\delta_4^a(\mathit{false}, a) & = & (\bot, \mathit{false}) \\
\delta_4^a(p, a) & = & (p \in a, [p \in a]) \\
\delta_4^a(\varphi \vee \psi, a) & = & \delta_4^a(\varphi, a) \vee \delta_4^a(\psi, a) \\
\delta_4^a(\varphi \wedge \psi, a) & = & \delta_4^a(\varphi, a) \wedge \delta_4^a(\psi, a) \\
\delta_4^a(\varphi\, U\, \psi, a) & = & \delta_4^a(\psi \vee (\varphi \wedge X(\varphi\, U\, \psi)), a) \\
 & = & \delta_4^a(\psi, a) \vee (\delta_4^a(\varphi, a) \wedge (\varphi\, U\, \psi)) \\
\delta_4^a(\varphi\, R\ \ \psi, a) & = & \delta_4^a(\psi \wedge (\varphi \vee \bar{X}(\varphi\, R\, \psi)), a) \\
 & = & \delta_4^a(\psi, a) \wedge (\delta_4^a(\varphi, a) \vee (\varphi\, R\, \psi)) \\
\delta_4^a(X\varphi, a) & = & (\bot^p, \varphi) \\
\delta_4^a(\bar{X}\varphi, a) & = & (\top^p, \varphi)
\end{array}
$$

Outline

- Runtime Verification
- Runtime Verification for LTL
    - LTL over Finite, Completed Words
    - LTL over Finite, Non-Completed Words: Impartiality
    - LTL over Non-Completed Words: Anticipation
    - LTL over Infinite Words: With Anticipation
    - Generalisations: LTL with modulo Constraints
    - Monitorable Properties
    - LTL with a Predictive Semantics
    - LTL wrap-up
- Extensions
- Monitoring Systems/Logging
- Steering
- Diagnosis
    - Ideas
    - RV and Diagnosis
- Conclusion

Anticipatory Semantics

Consider possible extensions of the non-completed word

Outline

- Runtime Verification
- Runtime Verification for LTL
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LTL for RV [BLS@FSTTCS'06]

Basic idea

- LTL over infinite words is commonly used for specifying correctness properties
- finite words in RV:
  prefixes of infinite, so-far unknown words
- re-use existing semantics

LTL for RV [BLS@FSTTCS'06]

Basic idea

- LTL over infinite words is commonly used for specifying correctness properties
- finite words in RV:
  prefixes of infinite, so-far unknown words
- re-use existing semantics

3-valued semantics for LTL over finite words

$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

Impartial Anticipation

Impartial

- Stay with $\top$ and $\bot$

Impartial Anticipation

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- Stay with $\top$ and $\bot$

Anticipatory

- Go for $\top$ or $\bot$
- Consider $XXX\mathit{false}$

$$\epsilon \quad \models \quad XXX\mathit{false}$$

Impartial Anticipation

Impartial

- Stay with $\top$ and $\bot$

Anticipatory

- Go for $\top$ or $\bot$
- Consider $XXXfalse$

$$\begin{array}{ccc} \epsilon & \models & XXXfalse \\ a & \models & XXfalse \end{array}$$

Impartial Anticipation

Impartial

- Stay with $\top$ and $\bot$

Anticipatory

- Go for $\top$ or $\bot$
- Consider $XXX\mathit{false}$

$$\begin{array}{lcl} \epsilon & \models & XXX\mathit{false} \\ a & \models & XX\mathit{false} \\ aa & \models & X\mathit{false} \end{array}$$

Impartial Anticipation

Impartial

- Stay with $\top$ and $\bot$

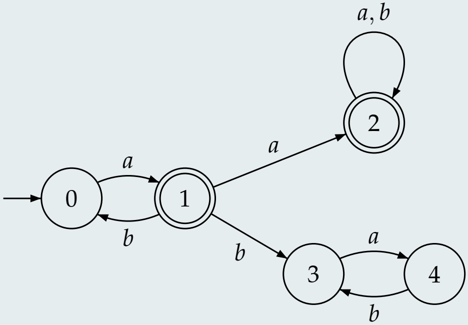
Anticipatory

- Go for $\top$ or $\bot$
- Consider $XXX\mathit{false}$

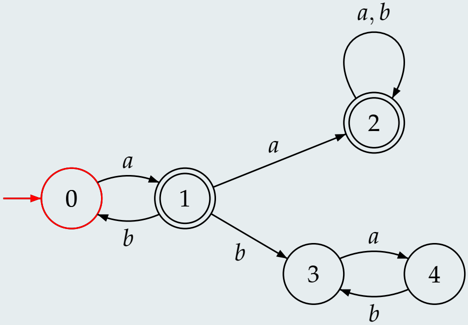
$$\begin{array}{lcl} \epsilon & \models & XXX\mathit{false} \\ a & \models & XX\mathit{false} \\ aa & \models & X\mathit{false} \\ aaa & \models & \mathit{false} \end{array}$$

$$[\epsilon \models XXX\mathit{false}] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : \epsilon\sigma \models XXX\mathit{false} \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : \epsilon\sigma \not\models XXX\mathit{false} \\ ? & \text{else} \end{cases}$$

Büchi automata (BA)



Büchi automata (BA)



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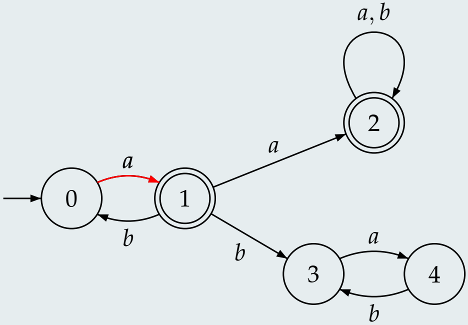
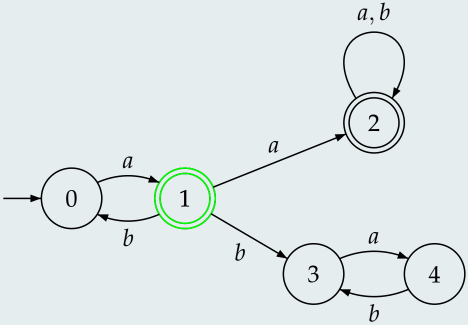


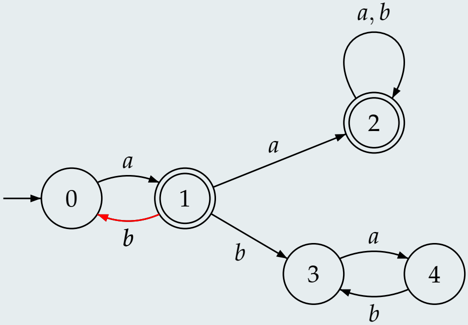
a

Büchi automata (BA)



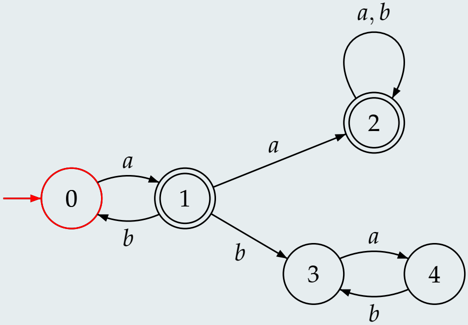
a

Büchi automata (BA)



$a\ b$

Büchi automata (BA)



a b

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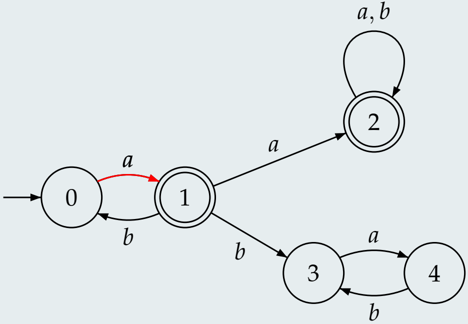

a b a

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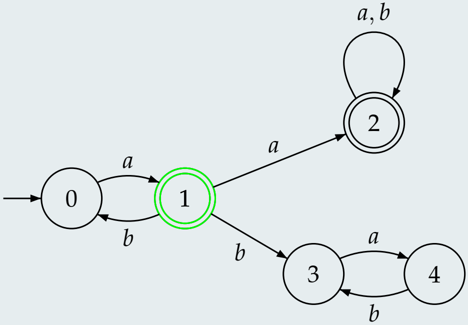
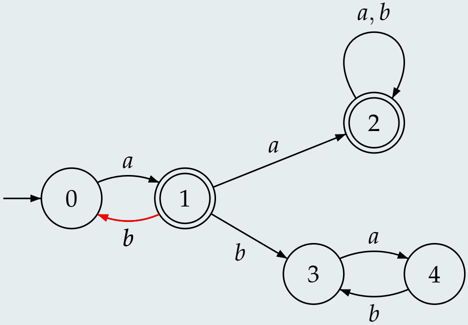


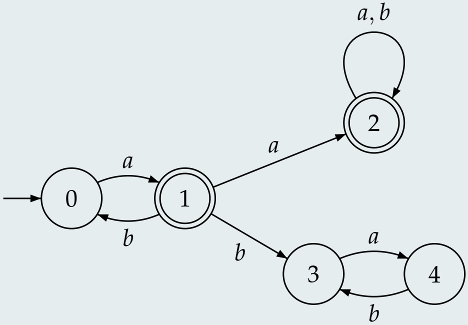
$a\ b\ a$

Büchi automata (BA)



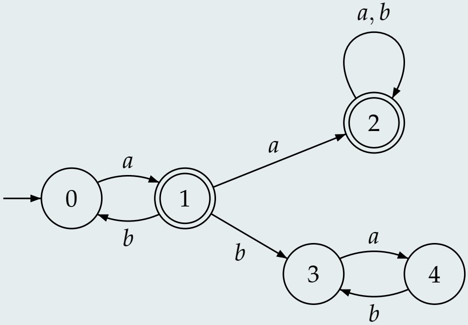
a b a b

Büchi automata (BA)



$a\ b\ a\ b \ldots$

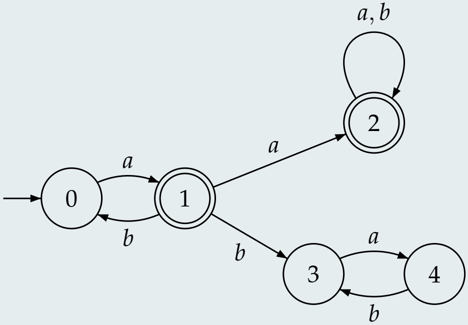
Büchi automata (BA)



$a\ b\ a\ b \dots$

$(ab)^\omega \in \mathcal{L}(\mathcal{A})$

Büchi automata (BA)



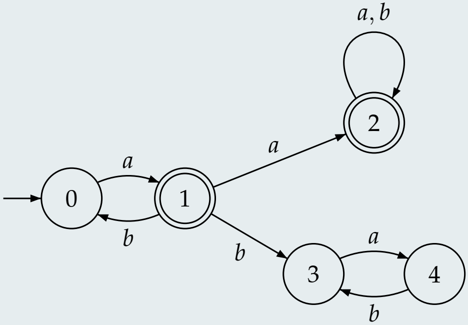
$a\ b\ a\ b\ \ldots$

$(ab)^\omega \in \mathcal{L}(\mathcal{A})$

$(ab)^* aa\{a,b\}^\omega \subseteq \mathcal{L}(\mathcal{A})$

Büchi automata (BA)

Emptiness test:



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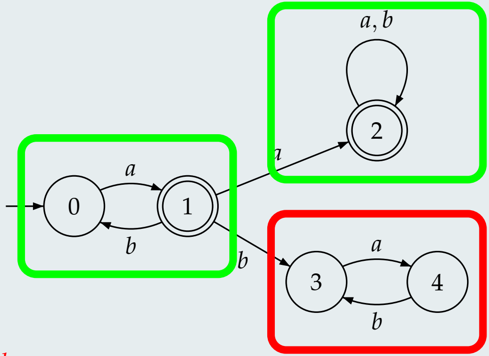
Büchi automata (BA)

Emptiness test: SCCC, Tarjan



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LTL to BA

[Vardi & Wolper '86]

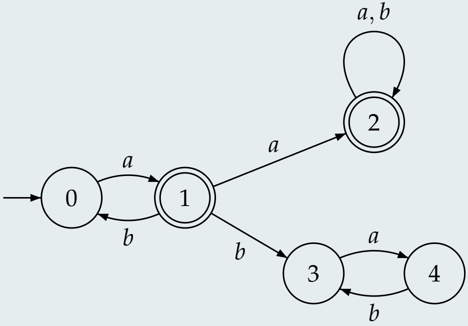
- Translation of an LTL formula φ into Büchi automata $\mathcal{A}_\varphi$ with

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

- Complexity: Exponential in the length of φ

Monitor construction – Idea I

$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$



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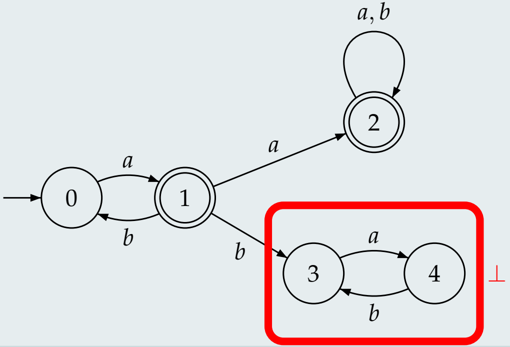

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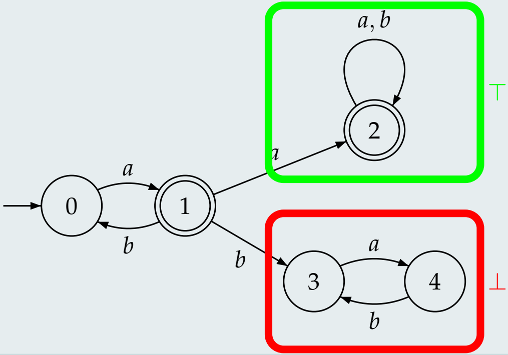

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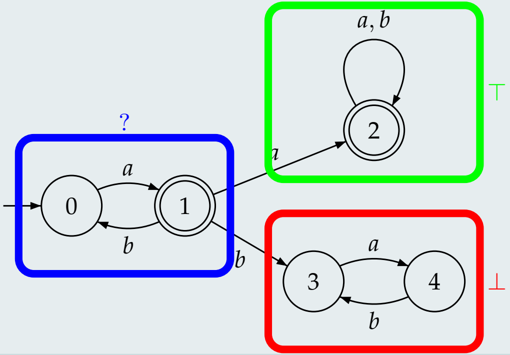
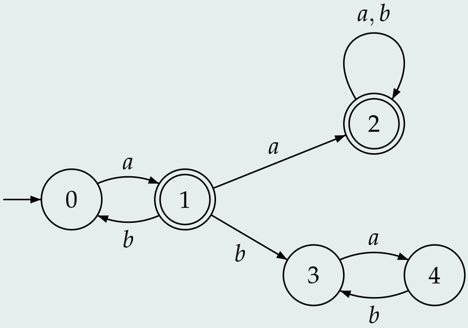
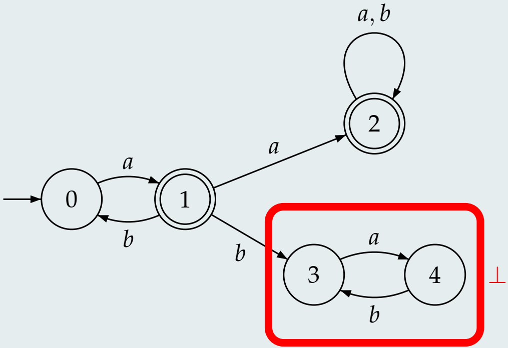


monitor construction – Idea II



monitor construction – Idea II



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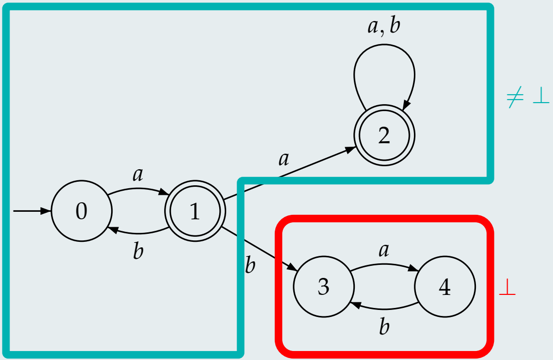
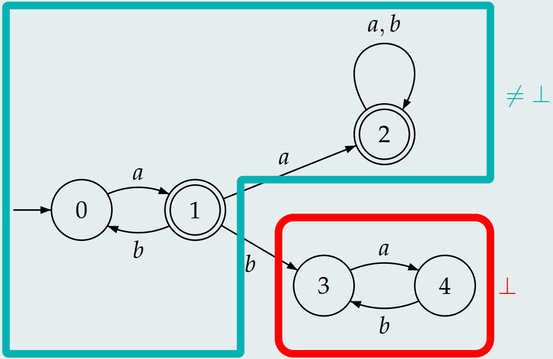


monitor construction – Idea II



NFA

$\mathcal{F}_\varphi : Q_\varphi \to \{\top, \bot\}$ Emptiness per state

The complete construction

The construction

$$\varphi \longrightarrow \mathrm{BA}^{\varphi} \longrightarrow \mathcal{F}^{\varphi} \longrightarrow \mathrm{NFA}^{\varphi}$$

Lemma

$$[u \models \varphi] = \begin{cases} \top & \\ \bot & \text{if } u \notin \mathcal{L}(\mathrm{NFA}^{\varphi}) \\ ? & \end{cases}$$

The complete construction

The construction

$$\varphi \longrightarrow \mathrm{BA}^{\varphi} \longrightarrow \mathcal{F}^{\varphi} \longrightarrow \mathrm{NFA}^{\varphi}$$

$$\neg\varphi$$

Lemma

$$[u \models \varphi] = \begin{cases} \top & \\ \bot & \text{if } u \notin \mathcal{L}(\mathrm{NFA}^{\varphi}) \\ ? & \end{cases}$$

The complete construction

The construction

$$\begin{tikzcd}
\varphi \arrow[r] & \mathrm{BA}^{\varphi} \arrow[r] & \mathcal{F}^{\varphi} \arrow[r] & \mathrm{NFA}^{\varphi} \\
\neg\varphi \arrow[r] & \mathrm{BA}^{\neg\varphi} \arrow[r] & \mathcal{F}^{\neg\varphi} \arrow[r] & \mathrm{NFA}^{\neg\varphi}
\end{tikzcd}$$

Lemma

$$[u \models \varphi] = \begin{cases} \top & \text{if } u \notin \mathcal{L}(\mathrm{NFA}^{\neg\varphi}) \\ \bot & \text{if } u \notin \mathcal{L}(\mathrm{NFA}^{\varphi}) \\ ? & \text{else} \end{cases}$$

The complete construction

The construction

$$\begin{tikzcd}
 & \varphi \arrow[r] & \mathrm{BA}^{\varphi} \arrow[r] & \mathcal{F}^{\varphi} \arrow[r] & \mathrm{NFA}^{\varphi} \\
\varphi \arrow[ur] \arrow[dr] & & & & \\
 & \neg\varphi \arrow[r] & \mathrm{BA}^{\neg\varphi} \arrow[r] & \mathcal{F}^{\neg\varphi} \arrow[r] & \mathrm{NFA}^{\neg\varphi}
\end{tikzcd}$$

The complete construction

The construction

$$\begin{tikzcd}
& \varphi \arrow[r] & \mathrm{BA}^{\varphi} \arrow[r] & \mathcal{F}^{\varphi} \arrow[r] & \mathrm{NFA}^{\varphi} \arrow[r] & \color{red}{\mathrm{DFA}^{\varphi}} \\
\varphi \arrow[ur] \arrow[dr] & & & & & \\
& \neg\varphi \arrow[r] & \mathrm{BA}^{\neg\varphi} \arrow[r] & \mathcal{F}^{\neg\varphi} \arrow[r] & \mathrm{NFA}^{\neg\varphi} \arrow[r] & \color{red}{\mathrm{DFA}^{\neg\varphi}}
\end{tikzcd}$$

The complete construction

The construction

$$\begin{tikzcd}
 & \varphi \arrow[r] & \mathrm{BA}^{\varphi} \arrow[r] & \mathcal{F}^{\varphi} \arrow[r] & \mathrm{NFA}^{\varphi} \arrow[r] & \mathrm{DFA}^{\varphi} \arrow[dr] & \\
\varphi \arrow[ur] \arrow[dr] & & & & & & M \\
 & \neg\varphi \arrow[r] & \mathrm{BA}^{\neg\varphi} \arrow[r] & \mathcal{F}^{\neg\varphi} \arrow[r] & \mathrm{NFA}^{\neg\varphi} \arrow[r] & \mathrm{DFA}^{\neg\varphi} \arrow[ur] &
\end{tikzcd}$$

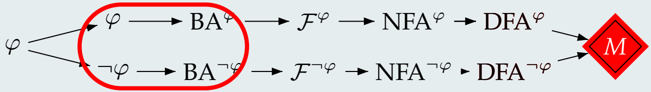
Complexity

The construction

$$\begin{tikzcd}
 & \varphi \arrow[r] & \mathrm{BA}^{\varphi} \arrow[r] & \mathcal{F}^{\varphi} \arrow[r] & \mathrm{NFA}^{\varphi} \arrow[r] & \mathrm{DFA}^{\varphi} \arrow[dr] & \\
\varphi \arrow[ur] \arrow[dr] & & & & & & \boxed{M} \\
 & \neg\varphi \arrow[r] & \mathrm{BA}^{\neg\varphi} \arrow[r] & \mathcal{F}^{\neg\varphi} \arrow[r] & \mathrm{NFA}^{\neg\varphi} \arrow[r] & \mathrm{DFA}^{\neg\varphi} \arrow[ur] &
\end{tikzcd}$$

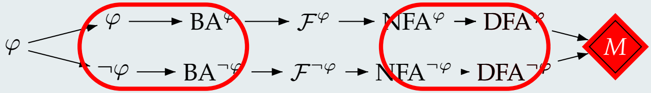
Complexity

The construction



Complexity

The construction



Complexity

The construction

$$\begin{tikzcd}
 & \varphi \arrow[r] & \mathrm{BA}^{\varphi} \arrow[r] & \mathcal{F}^{\varphi} \arrow[r] & \mathrm{NFA}^{\varphi} \arrow[r] & \mathrm{DFA}^{\varphi} \arrow[dr] & \\
\varphi \arrow[ur] \arrow[dr] & & & & & & \boxed{M} \\
 & \neg\varphi \arrow[r] & \mathrm{BA}^{\neg\varphi} \arrow[r] & \mathcal{F}^{\neg\varphi} \arrow[r] & \mathrm{NFA}^{\neg\varphi} \arrow[r] & \mathrm{DFA}^{\neg\varphi} \arrow[ur] &
\end{tikzcd}$$

Complexity

$$|M| \leq 2^{2^{|\varphi|}}$$

Complexity

The construction

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\end{tikzcd}$$

Complexity

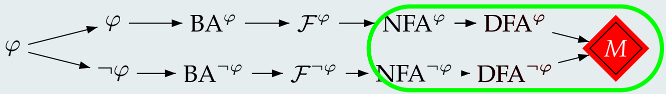
$$|M| \leq 2^{2^{|\varphi|}}$$

Optimal result!

FSM can be minimised (Myhill-Nerode)

On-the-fly Construction

The construction



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\end{tikzcd}$$

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- Runtime Verification
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Towards richer and more expressive logics [DLS@ATVA'08]

Many linear-time logics

- LTL with Past

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Many linear-time logics

- LTL with Past
- linear-time μ-calculus

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- RLTL
- LTL with integer constraints

$$G(fopen_x \to ((x = Xx)\ U\ fclose_x))$$

Linear-time Logic

Definition (Linear-time Logic)

A linear-time logic L defines

- a set F_L of L-formulae and
- a two-valued semantics $\models_L$.

Every L-formula $\varphi \in F_L$ has an associated and possibly infinite alphabet Σ_φ. Moreover, for every formula $\varphi \in F_L$ and every word $\sigma \in \Sigma_\varphi^\omega$, we require

(L1) $\forall \varphi \in F_L \ : \ \neg\varphi \in F_L.$

(L2) $\forall \sigma \in \Sigma_\varphi^\omega \ : \ (\sigma \models_L \varphi \quad \Leftrightarrow \quad \sigma \not\models_L \neg\varphi).$

Anticipation Semantics

Definition (Anticipation Semantics)

Let L be a linear-time logic. We define the anticipation semantics $[\pi \models \varphi]_L$ of an L-formula $\varphi \in F_L$ and a finite word $\pi \in \Sigma_\varphi^*$ with

$$[\pi \models \varphi]_L = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma_\varphi^\omega : \pi\sigma \models_L \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma_\varphi^\omega : \pi\sigma \not\models_L \varphi \\ ? & \text{otherwise} \end{cases}$$

Evaluation using decide

decide

$$[\pi \models \varphi]_L = \begin{cases} \top & \text{if } \mathsf{decide}_{\neg\varphi}(\pi) = \bot \\ \bot & \text{if } \mathsf{decide}_{\varphi}(\pi) = \bot \\ ? & \text{otherwise} \end{cases}$$

where $\mathsf{decide}_\varphi(\pi)$ is defined to return $\top$ for $\varphi \in F_L$ and $\pi \in \Sigma_\varphi$ if $\exists \sigma \in \Sigma_\varphi^\omega \ : \ \pi\sigma \models_L \varphi$ holds, and $\bot$ otherwise.

The automata theoretic approach to SAT

Definition (Satisfiability Check by Automata Abstraction)

Given a linear-time logic L with its formulae F_L, the satisfiability check by automata abstraction proceeds as follows. For formula $\varphi \in F_L$,

1. define alphabet abstraction $\Sigma_\varphi \to \bar{\Sigma}_\varphi$ finite, abstract alphabet
2. define a word abstraction $\alpha(\cdot) : \Sigma_\varphi^\omega \to \bar{\Sigma}_\varphi^\omega$
3. define an automaton construction $\varphi \mapsto \omega$-automaton $\mathcal{A}_\varphi$ over $\bar{\Sigma}_\varphi$ such that for all $\bar{\sigma} \in \bar{\Sigma}_\varphi^\omega$ it holds

   $$\bar{\sigma} \in \mathcal{L}(\mathcal{A}_\varphi) \text{ iff } \exists \sigma \in \Sigma^\omega : \bar{\sigma} = \alpha(\sigma) \text{ and } \sigma \models \varphi$$

   Then

   $$\varphi \text{ satisfiable iff } \mathcal{L}(\mathcal{A}_\varphi) \neq \emptyset \text{ iff non-empty}(\mathcal{A}_\varphi)$$

From finite to infinite

Definition (extrapolate)

$$\text{extrapolate}(\pi) = \left\{ \alpha(\pi\sigma)^{0\ldots i} \mid i+1 = |\pi|, \sigma \in \Sigma^\omega \right\}$$

Definition (Accuracy of Abstract Automata)

accuracy of abstract automata property holds, if, for all $\pi \in \Sigma^*$,

- $(\exists \sigma : \pi\sigma \models_L \varphi) \Rightarrow (\exists \bar{\pi} \exists \bar{\sigma} : \bar{\pi}\bar{\sigma} \in \mathcal{L}(\mathcal{A}_\varphi))$ with $\bar{\pi} \in \text{extrapolate}(\pi)$,
- $(\exists \bar{\sigma} : \bar{\pi}\bar{\sigma} \in \mathcal{L}(\mathcal{A}_\varphi)) \Rightarrow (\exists \pi \exists \sigma : \pi\sigma \models_L \varphi)$ with $\bar{\pi} \in \text{extrapolate}(\pi)$.

Non-incremental version

Theorem (Correctness of decide)

Given a satisfiability check by automata abstraction for a linear-time logic L satisfying the accuracy of automata property, we have

$$\mathsf{decide}(\pi) = \mathsf{non\text{-}empty}\left(\bigcup_{q \in Q_0, \bar{\pi} \in \mathsf{extrapolate}(\pi)} \delta(q, \bar{\pi}) \right)$$

Faithful abstraction

Definition (Forgettable Past and Faithful Abstraction)

Given α of a satisfiability check by automata abstraction. We say that

- α satisfies the forgettable past property, iff

$$\alpha(\pi a \sigma)^{i+1\dots i+1} = \alpha(a\sigma)^{0\dots 0}$$

  for all $\pi \in \Sigma^*$, $|\pi| = i+1$, $a \in \Sigma$, and $\sigma \in \Sigma^\omega$.

- α is called faithful, iff for all $\pi \in \Sigma^*$, $|\pi| = i+1$, $a \in \Sigma$, $\sigma, \sigma' \in \Sigma^\omega$ for which there is some $\sigma'' \in \Sigma^\omega$ with $\alpha(\pi\sigma)^{0\dots i}\alpha(a\sigma')^{0\dots 0} = \alpha(\sigma'')^{0\dots i+1}$ there also exists a $\sigma''' \in \Sigma^\omega$ with

$$\alpha(\pi\sigma)^{0\dots i}\alpha(a\sigma')^{0\dots 0} = \alpha(\pi a \sigma''')^{0\dots i+1}$$

Incremental version

Theorem (Incremental Emptiness for Extrapolation)

Let $\mathcal{A}$ be a Büchi automaton obtained via a satisfiability check by automata abstraction satisfying the accuracy of automaton abstraction property with a faithful abstraction function having the forgettable past property. Then, for all $\pi \in \Sigma^*$ and $a \in \Sigma$, it holds

$$\mathcal{L}(\mathcal{A}(\mathsf{extrapolate}(\pi a))) = \mathcal{L}(\mathcal{A}(\mathsf{extrapolate}(\pi)\mathsf{extrapolate}(a)))$$

Further logics

Indeed works

- LTL with Past
- linear-time μ-calculus
- RLTL
- *LTL* with integer constraints

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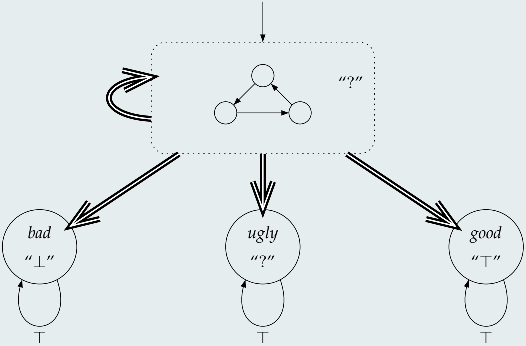
Monitorability

When does anticipation help?

Monitors revisited

Structure of Monitors



Monitors revisited

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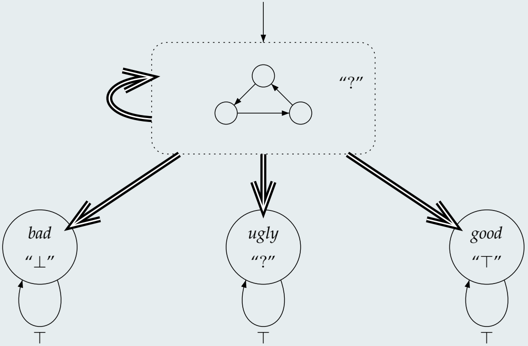

Classification of Prefixes of Words

- Bad prefixes [Kupferman & Vardi'01]

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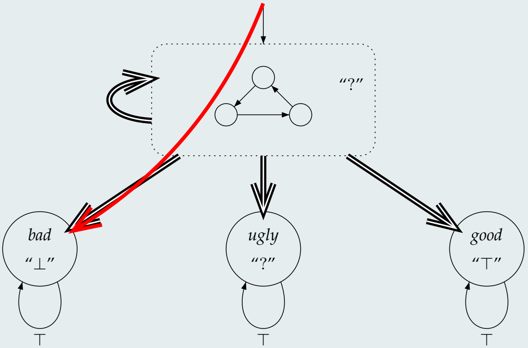

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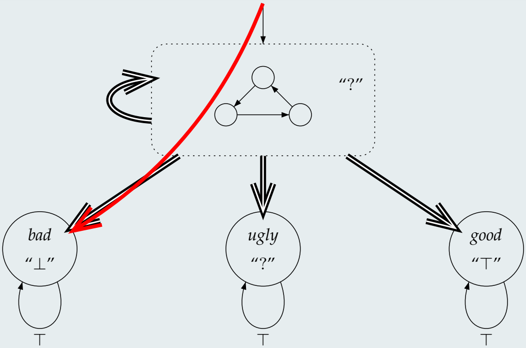

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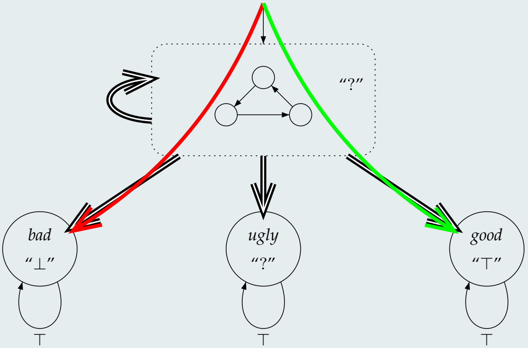

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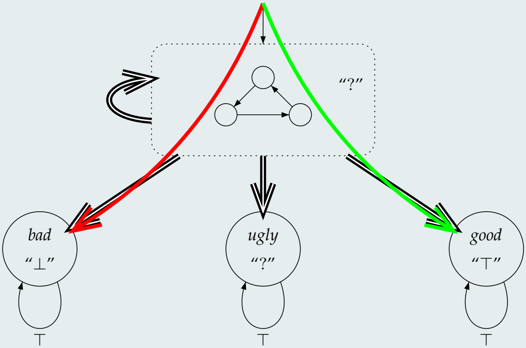

Classification of Prefixes of Words

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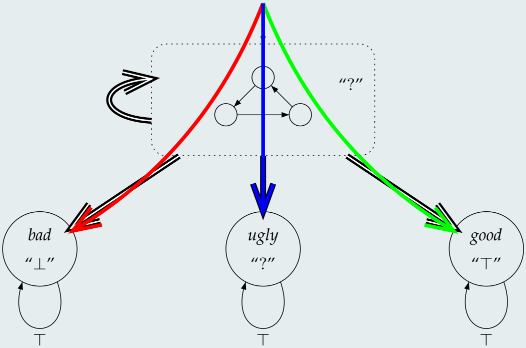
- Good prefixes [Kupferman & Vardi'01]
- Ugly prefixes

Monitors revisited

Structure of Monitors



Classification of Prefixes of Words

- Bad prefixes [Kupferman & Vardi'01]
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- Ugly prefixes

Monitorable

Non-Monitorable [Pnueli & Zaks'07]

φ is non-monitorable after u, if u cannot be extended to a bad oder good prefix.

Monitorable

φ is monitorable if there is no such u.

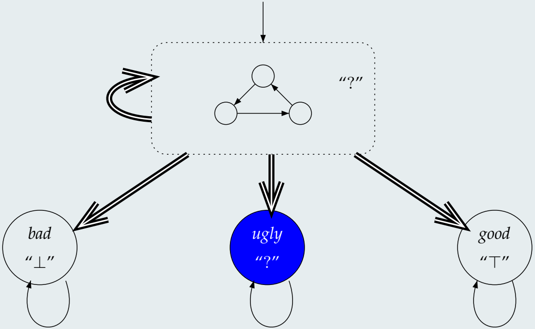
Monitorable

Non-Monitorable [Pnueli & Zaks'07]

φ is non-monitorable after u, if u cannot be extended to a bad oder good prefix.

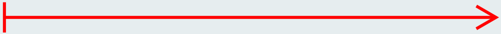
Monitorable

φ is monitorable if there is no such u.



Monitorable Properties

Safety Properties



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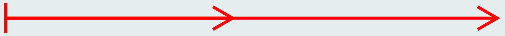

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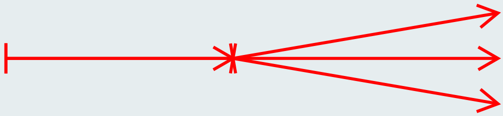

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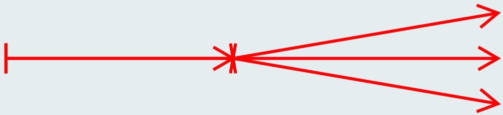
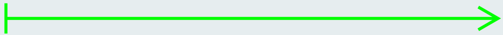


Co-Safety Properties



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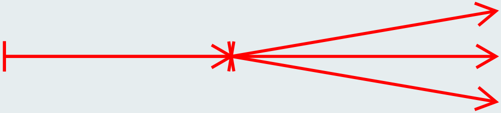

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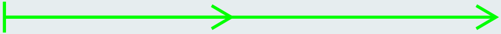

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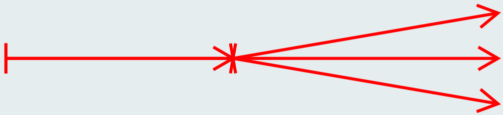

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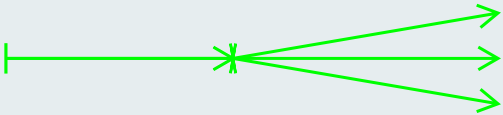

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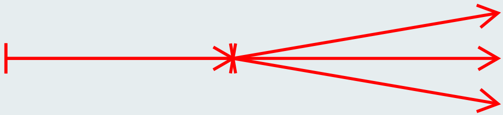

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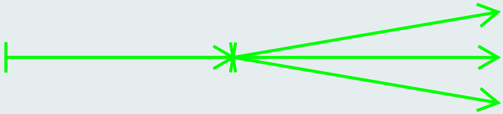

Note

Safety and Co-Safety Properties are monitorable

Safety- and Co-Safety-Properties

Theorem

The class of monitorable properties

- comprises safety- and co-safety properties, but
- is strictly larger than their union.

Proof

Consider $((p \vee q)Ur) \vee Gp$

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Fusing model checking and runtime verification

LTL with a predictive semantics

Recall anticipatory LTL semantics

The truth value of a LTL$_3$ formula φ wrt. u, denoted by $[u \models \varphi]$, is an element of $\mathbb{B}_3$ defined by

$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \not\models \varphi \\ ? & \text{otherwise.} \end{cases}$$

Applied to the empty word

Empty word ϵ

$$\begin{array}{ll} & [\epsilon \models \varphi]_{\mathcal{P}} = \top \\ \text{iff} & \forall \sigma \in \Sigma^{\omega} \text{ with } \epsilon\sigma \in \mathcal{P} : \epsilon\sigma \models \varphi \\ \text{iff} & \mathcal{L}(\mathcal{P}) \models \varphi \end{array}$$

RV more difficult than MC?

Then runtime verification implicitly answers model checking

Abstraction

An over-abstraction or and over-approximation of a program $\mathcal{P}$ is a program $\hat{\mathcal{P}}$ such that $\mathcal{L}(\mathcal{P}) \subseteq \mathcal{L}(\hat{\mathcal{P}}) \subseteq \Sigma^\omega$.

Predictive Semantics

Definition (Predictive semantics of LTL)

Let $\mathcal{P}$ be a program and let $\hat{\mathcal{P}}$ be an over-approximation of $\mathcal{P}$. Let $u \in \Sigma^*$ denote a finite trace. The *truth value* of u and an LTL_3 formula φ wrt. $\hat{\mathcal{P}}$, denoted by $[u \models_{\hat{\mathcal{P}}} \varphi]$, is an element of $\mathbb{B}_3$ and defined as follows:

$$[u \models_{\hat{\mathcal{P}}} \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega \text{ with } u\sigma \in \hat{\mathcal{P}} : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega \text{ with } u\sigma \in \hat{\mathcal{P}} : u\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

We write $\mathrm{LTL}_{\mathcal{P}}$ whenever we consider LTL formulas with a predictive semantics.

Properties of Predictive Semantics

Let $\hat{\mathcal{P}}$ be an over-approximation of a program $\mathcal{P}$ over Σ, $u \in \Sigma^*$, and $\varphi \in$ LTL.

- Model checking is more precise than RV with the predictive semantics:

$$\mathcal{P} \models \varphi \text{ implies } [u \models_{\hat{\mathcal{P}}} \varphi] \in \{\top, ?\}$$

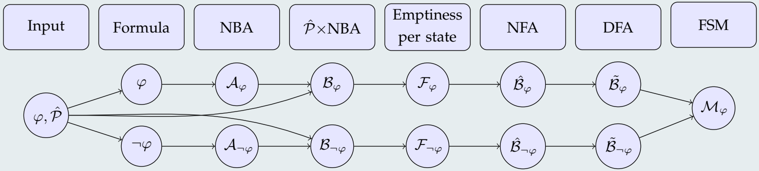
- RV has no false negatives: $[u \models_{\hat{\mathcal{P}}} \varphi] = \bot$ implies $\mathcal{P} \not\models \varphi$
- The predictive semantics of an LTL formula is more precise than LTL$_3$:

$$\begin{array}{lcl} [u \models \varphi] = \top & \text{implies} & [u \models_{\hat{\mathcal{P}}} \varphi] = \top \\ [u \models \varphi] = \bot & \text{implies} & [u \models_{\hat{\mathcal{P}}} \varphi] = \bot \end{array}$$

The reverse directions are in general not true.

Monitor generation

The procedure for getting $[u \models_{\hat{\mathcal{P}}} \varphi]$ for a given φ and over-approximation $\hat{\mathcal{P}}$



Input

Formula

NBA

$\hat{\mathcal{P}}\times$NBA

Emptiness per state

NFA

DFA

FSM

$\varphi, \hat{\mathcal{P}}$

φ

$\neg\varphi$

$\mathcal{A}_\varphi$

$\mathcal{A}_{\neg\varphi}$

$\mathcal{B}_\varphi$

$\mathcal{B}_{\neg\varphi}$

$\mathcal{F}_\varphi$

$\mathcal{F}_{\neg\varphi}$

$\hat{\mathcal{B}}_\varphi$

$\hat{\mathcal{B}}_{\neg\varphi}$

$\tilde{\mathcal{B}}_\varphi$

$\tilde{\mathcal{B}}_{\neg\varphi}$

$\mathcal{M}_\varphi$

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Intermediate Summary

Semantics

- completed traces
  - two valued semantics
- non-completed traces
  - Impartiality
    - at least three values
  - Anticipation
    - finite traces
    - infinite traces
    - . . .
    - monitorability
  - Prediction

Monitors

- left-to-right
- time versus space trade-off
  - rewriting
  - alternating automata
  - non-deterministic automata
  - deterministic automata

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Extensions

LTL is just half of the story

Extensions

LTL with data

- J-LO

Extensions

LTL with data

- J-LO
- MOP (parameterized LTL)

Extensions

LTL with data

- J-LO
- MOP (parameterized LTL)
- RV for LTL with integer constraints

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Further “rich” approaches

- LOLA

Extensions

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Further dimensions

- real-time

Extensions

LTL with data

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Further dimensions

- real-time
- concurrency

Extensions

LTL with data

- J-LO
- MOP (parameterized LTL)
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Further “rich” approaches

- LOLA
- Eagle (etc.)

Further dimensions

- real-time
- concurrency
- distribution

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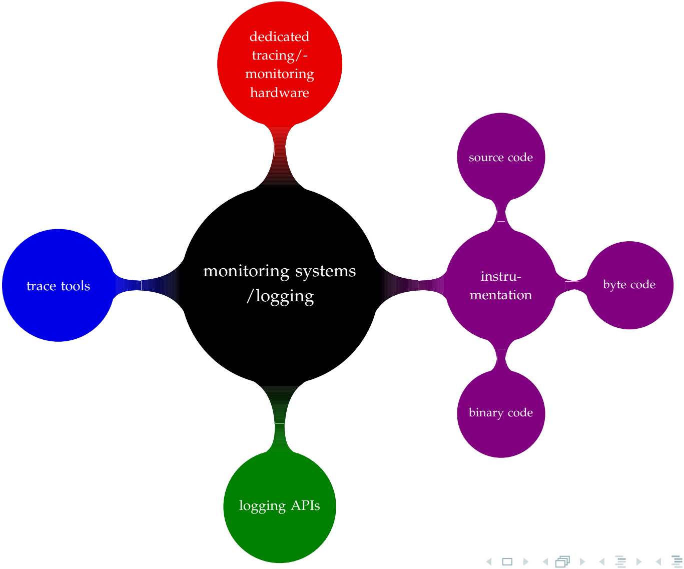
Monitoring Systems/Logging: Overview



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- LTL over Non-Completed Words: Anticipation
- LTL over Infinite Words: With Anticipation
- Generalisations: LTL with modulo Constraints
- Monitorable Properties
- LTL with a Predictive Semantics
- LTL wrap-up

Extensions

Monitoring Systems/Logging

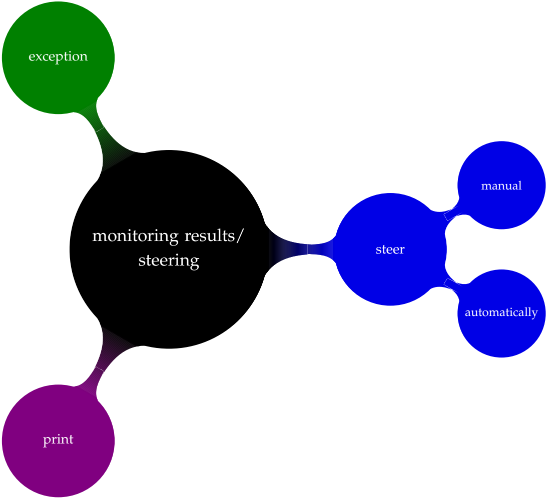
Steering

Diagnosis

- Ideas
- RV and Diagnosis

Conclusion

Monitoring Systems/Logging: Overview



React!

Runtime Verification

Observe—do not react

Realising dynamic systems

- self-healing systems
- adaptive systems, self-organising systems
- . . .

React!

Runtime Verification

Observe—do not react

Realising dynamic systems

- self-healing systems
- adaptive systems, self-organising systems
- ...
- use monitors for observation—then react

jMOP [Rosu et al.]

Java Implementation

```
class Resource {
/*@
     scope = class
     logic = PTLTL
     {
      Event authenticate: end(exec(*
authenticate()));
      Event use: begin(exec(* access()));
      Formula : use -> <*> authenticate
     }
     violation Handler {
       @this.authenticate();
     }
@*/
void authenticate() {...}
void access() {...}
...
}
```

Where

How

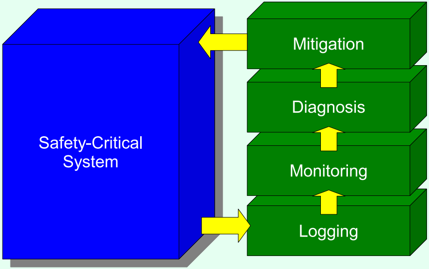
what

What if

Runtime Reflection [Bauer, L., Schallhart@ASWEC'06]

Monitor-based Runtime Reflection

Software Architecture Pattern



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Diagnosis

Main Ideas

- Knowledge base
- Knowledge
- Explanation of Knowledge with Respect to the Knowledge base

Diagnosis

Main Ideas

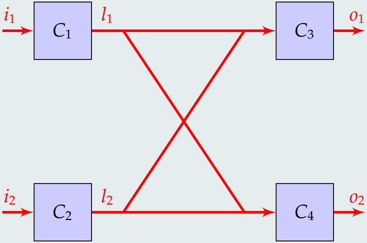
- Knowledge base
- Knowledge
- Explanation of Knowledge with Respect to the Knowledge base

Here

- System description
- Observations
- Diagnosis: Explanation of the Observations with respect to the System description

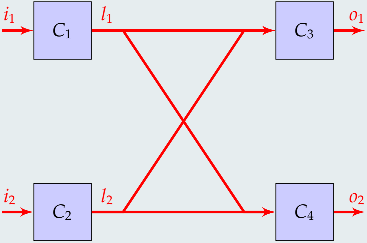
System Description in First-Order Logic

Example



System Description in First-Order Logic

Example

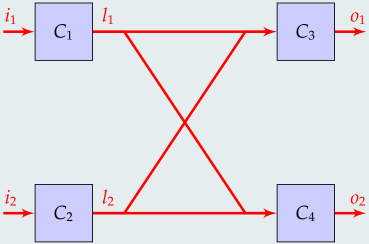


Formally

$$\begin{aligned} SD \quad = \quad & \quad ok(i_1) \land \neg AB(C_1) \rightarrow l_1 = C_1(i_1) \\ \land & \quad ok(i_2) \land \neg AB(C_2) \rightarrow l_2 = C_2(i_2) \\ \land & \quad ok(l_1) \land ok(l_2) \land \neg AB(C_3) \rightarrow o_1 = C_3(l_1, l_2) \\ \land & \quad ok(l_1) \land ok(l_2) \land \neg AB(C_4) \rightarrow o_2 = C_4(l_1, l_2) \end{aligned}$$

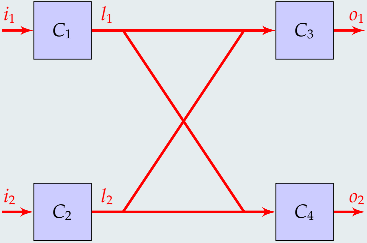
System Description in Propositional Logic

Example



System Description in Propositional Logic

Example

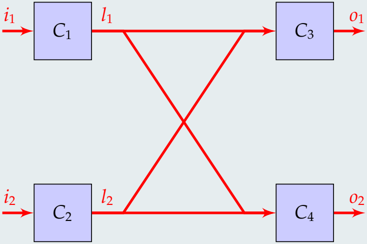


Propositional Logic

$$\begin{aligned} SD \quad = & \quad i_1 \land \neg C_1 \to l_1 \\ \land & \quad i_2 \land \neg C_2 \to l_2 \\ \land & \quad l_1 \land l_2 \land \neg C_3 \to o_1 \\ \land & \quad l_1 \land l_2 \land \neg C_4 \to o_2 \end{aligned}$$

Observation

Example



Observation

(Truth) values for (some of) the propositions involved

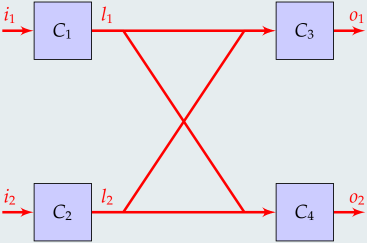
Formally: a formula OBS

Observation

$\neg o_1 \wedge i_1 \wedge i_2 \wedge o_2$

Diagnosis

Example

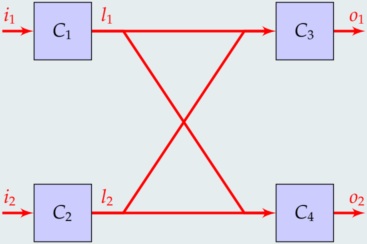


Diagnosis

A minimal set of components such that $SD \wedge OBS \wedge \Delta$ is satisfiable, where Δ encodes the chosen components.

Example

Example



Propositional Logic

$$\begin{array}{rcl} SD & = & i_1 \wedge \neg C_1 \to l_1 \\ & \wedge & i_2 \wedge \neg C_2 \to l_2 \\ & \wedge & l_1 \wedge l_2 \wedge \neg C_3 \to o_1 \\ & \wedge & l_1 \wedge l_2 \wedge \neg C_4 \to o_2 \end{array}$$

Observations

$\neg o_1 \wedge i_1 \wedge i_2 \wedge o_2$

Example

Propositional Logic

$$
\begin{aligned}
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\land & \quad l_1 \land l_2 \land \neg C_4 \to o_2
\end{aligned}
$$

Observations

$\neg o_1 \land i_1 \land i_2 \land o_2$

CNF

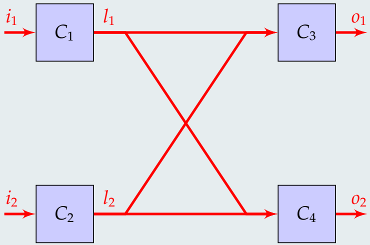
$$
\begin{aligned}
SD \quad = & \quad \neg i_1 \lor C_1 \lor l_1 \\
\land & \quad \neg i_2 \lor C_2 \lor l_2 \\
\land & \quad \neg l_1 \lor \neg l_2 \lor C_3 \lor o_1 \\
\land & \quad \neg l_1 \lor \neg l_2 \lor C_4 \lor o_2
\end{aligned}
$$

SD ∧ Observations

$$
\begin{aligned}
SD \quad = & \quad C_1 \lor l_1 \\
\land & \quad C_2 \lor l_2 \\
\land & \quad \neg l_1 \lor \neg l_2 \lor C_3 \\
\land & \\
\land & \quad \neg o_1 \land i_1 \land i_2 \land o_2
\end{aligned}
$$

Example

Example



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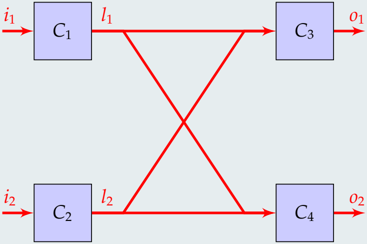

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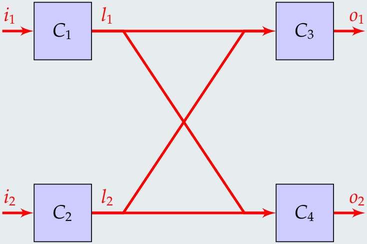

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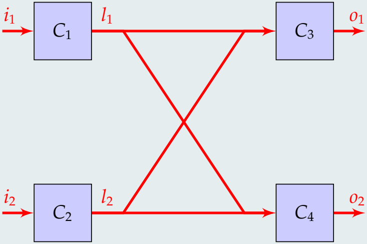

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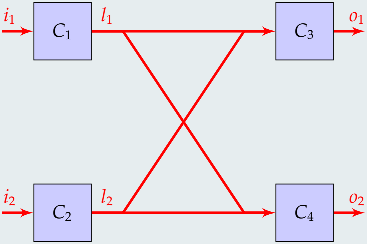

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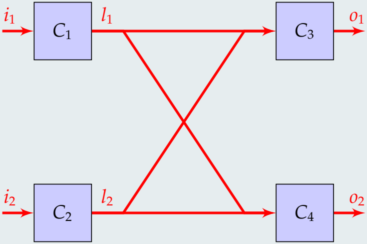

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Example

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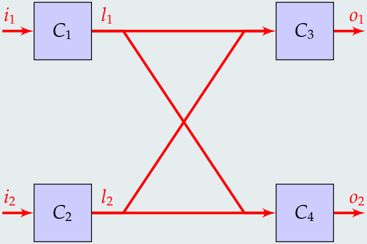

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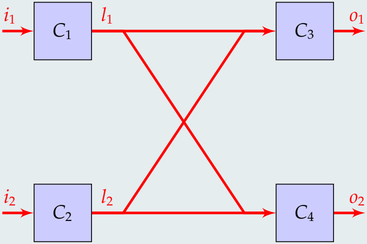
Diagnoses

- $\Delta_1 = \{C_1\}$

Example

Example



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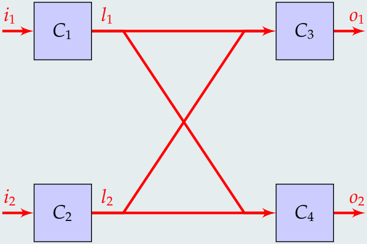
Diagnoses

- $\Delta_1 = \{C_1\}$
- $\Delta_2 = \{C_2\}$

Example

Example



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Diagnoses

- $\Delta_1 = \{C_1\}$
- $\Delta_2 = \{C_2\}$
- $\Delta_3 = \{C_3\}$

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Monitors yield Obervations

We have. . .

- Monitor reports $\perp$ $\rightsquigarrow$ line is false

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- Monitor reports $\bot \rightsquigarrow$ line is false
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Oniscent Monitors

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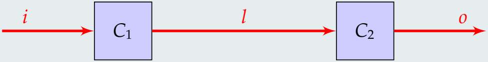

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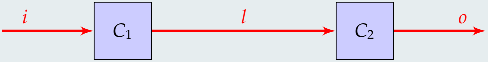

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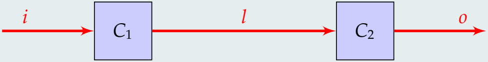
Oniscent Monitors

Example



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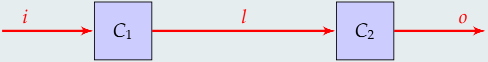
Observation: $i \wedge \neg o$

$$SD = C_1 \vee l \quad \wedge \quad \neg l \vee C_2$$

Oniscent Monitors

Example



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Diagnoses: C_2 or C_1

Oniscent Monitors

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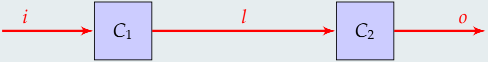

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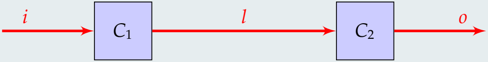
$$\begin{aligned} SD &= & C_1 \lor l \\ & \land & \neg l \lor C_2 \end{aligned}$$

Diagnoses: C_2 or C_1

If additionally l known to be correct, only C_2 diagnosed.

Oniscent Monitors

Example



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$\rightsquigarrow$ notion of omniscent diagnoses

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Conclusion

Summary

- RV for Failure detection
  - various, multi-valued approaches
  - various existing systems
  - does generally identifies failure detection and identification
- Diagonis for Failure identification?

Future work

What is the *right* combination?

That’s it!

Thanks! - Comments?

That's it!

Thanks! - Comments?