Temporal logics for multi-agent systems

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LSV, CNRS & ENS Cachan, France

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Lyon, 21-22 January 2013

Verification of computerised systems

- Computers are everywhere

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- Bugs are everywhere...

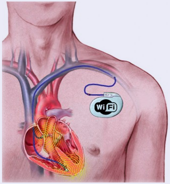

News

Toyota to recall Prius hybrids over ABS software

See video, below

By Martyn Williams
February 9, 2010 04:59 AM ET Comments (6) Recommended (15) Like

IDG News Service - Toyota plans to recall around 400,000 of its Prius hybrid cars to replace software that controls the antilock braking system (ABS), the auto maker said Tuesday.



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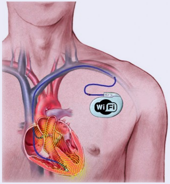
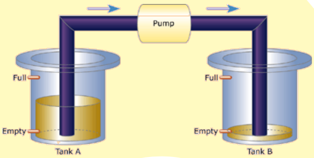


- Verification should be everywhere!

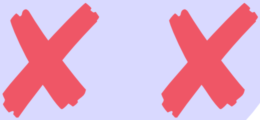
Model checking and synthesis

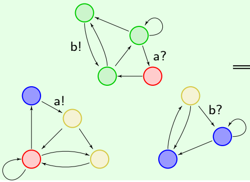
system:



[http://www.embedded.com]

property:



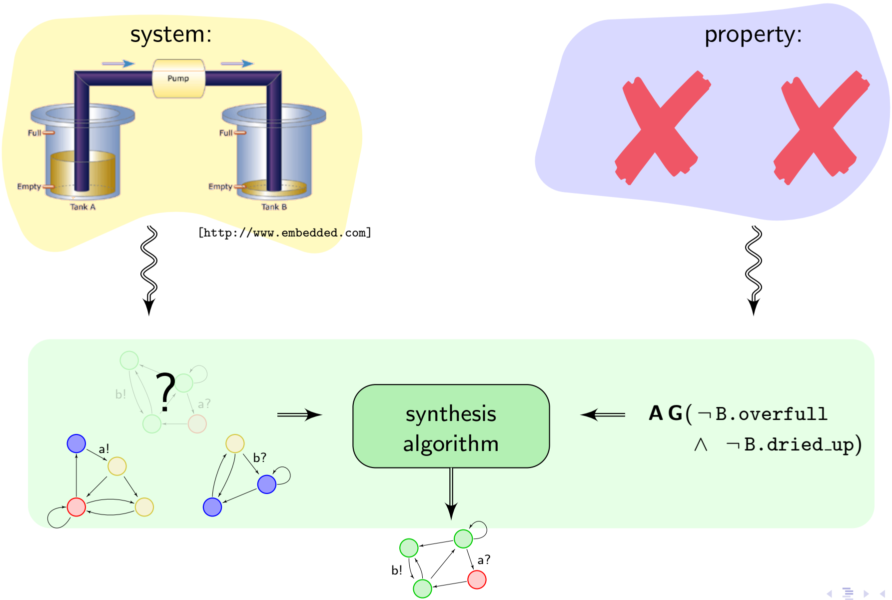


model-checking algorithm

$\mathbf{A\,G}(\neg\,\texttt{B.overfull} \;\wedge\; \neg\,\texttt{B.dried\_up})$

yes/no

Model checking and synthesis



Outline of the presentation

1. Introduction
   $\leadsto$ formal verification model checking and synthesis

2. Classical temporal logics: CTL and LTL
   $\leadsto$ expressing properties of “closed” systems

3. Temporal logics for games: ATL
   $\leadsto$ expressing properties of interacting systems
   extensions to non-zero-sum games

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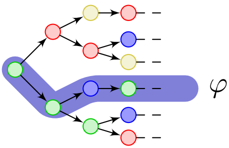

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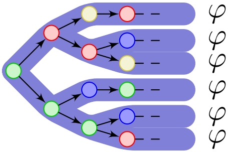

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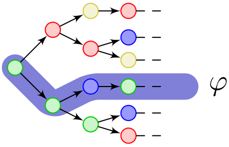
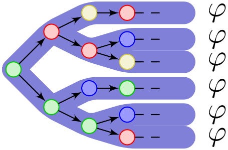
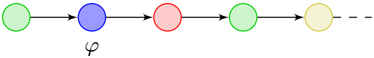
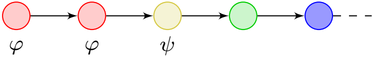
$\mathbf{E}\varphi$ 

$\mathbf{A}\varphi$ 

- **temporal modalities:**

$\mathbf{X}\,\varphi$ 

"next φ"

$\varphi\ \mathbf{U}\ \psi$ 

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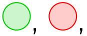
- **atomic propositions:**  , …
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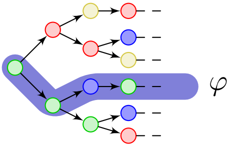
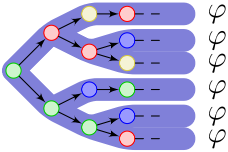
Eφ 

Aφ 

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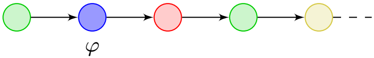
X φ 

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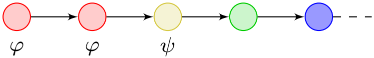
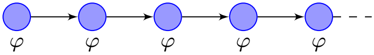
φ **U** ψ 

"φ until ψ"

`true` **U** $\varphi \equiv$ **F** φ 

"eventually φ"

$\neg$ **F** $\neg\varphi \equiv$ **G** φ 

"always φ"

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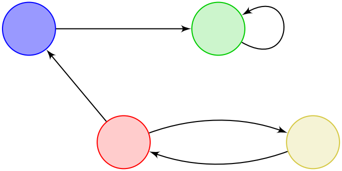

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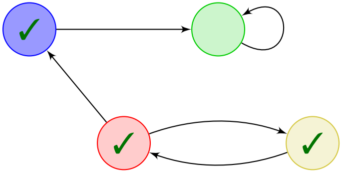

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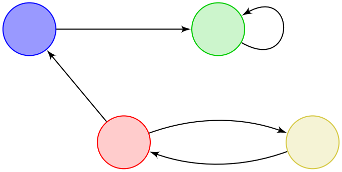

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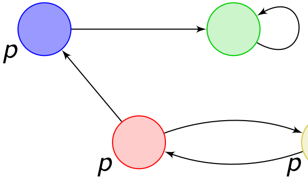

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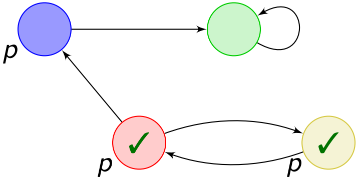

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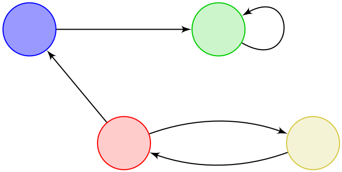

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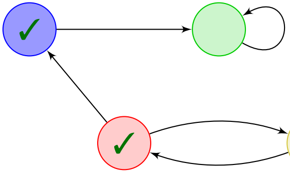

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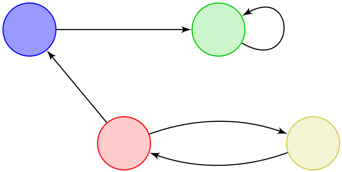

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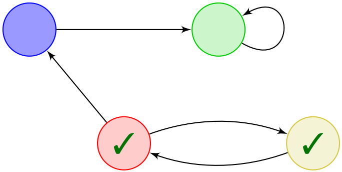

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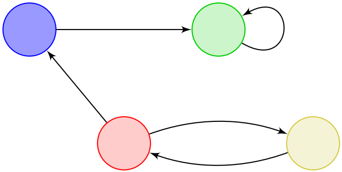

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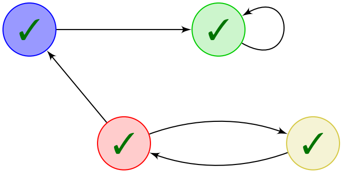

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Reasoning about multi-agent systems

Concurrent games

A concurrent game is made of

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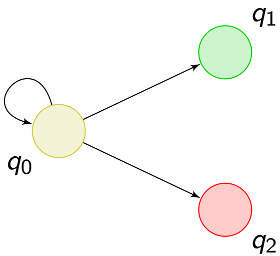

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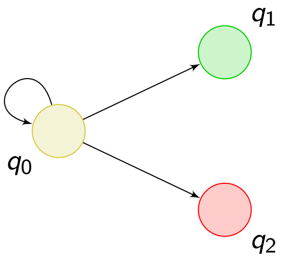

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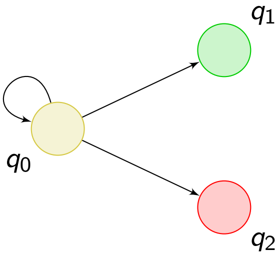

		player 1		
				
player 2		q_0	q_2	q_1
		q_1	q_0	q_2
		q_2	q_1	q_0

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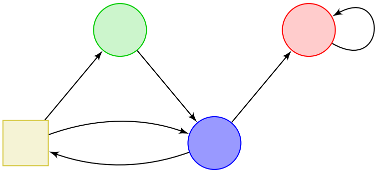
Turn-based games

A turn-based game is a game where only one agent plays at a time.



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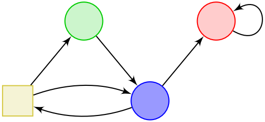

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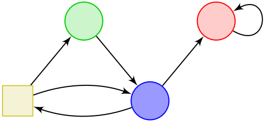

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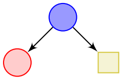

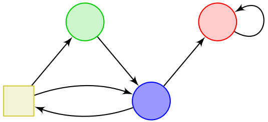

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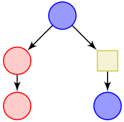

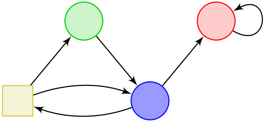

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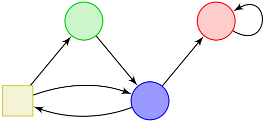

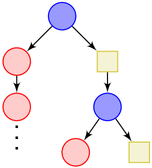

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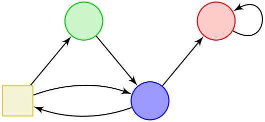

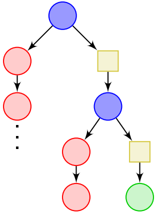

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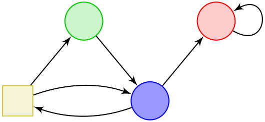

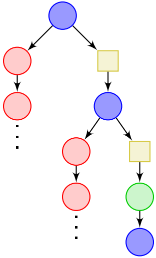

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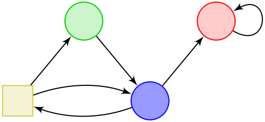

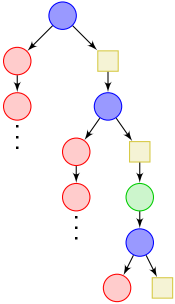

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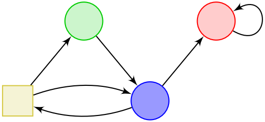

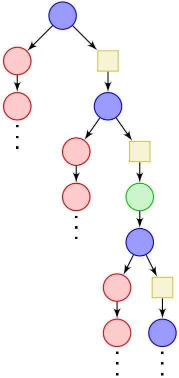

Alternating-time Temporal Logic

ATL formulas are built inductively using atomic propositions, Boolean combinations, temporal modalities **X** and **U**, and strategy quantifiers:

$$\langle\!\langle A \rangle\!\rangle\, \varphi \text{ expresses that } A \text{ has a strategy to enforce } \varphi.$$

Alternating-time Temporal Logic

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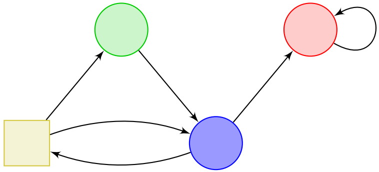

- $\langle\!\langle \bigcirc \rangle\!\rangle\ \mathbf{F}\ \bigcirc$

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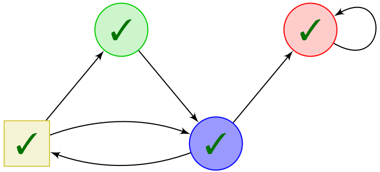

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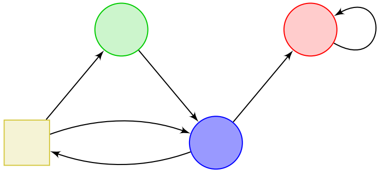

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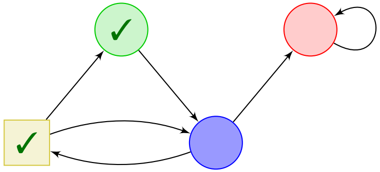

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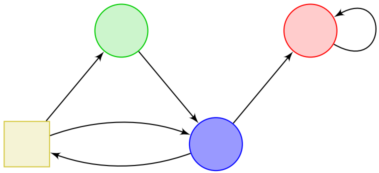

- $\langle\!\langle \bigcirc \rangle\!\rangle\ \mathbf{F}\ \bigcirc$
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- $\langle\!\langle \bigcirc \rangle\!\rangle\ \mathbf{G} (\ \langle\!\langle \square \rangle\!\rangle\ \mathbf{F}\ \bigcirc)$

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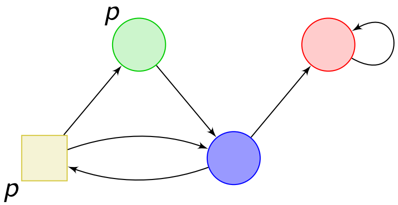

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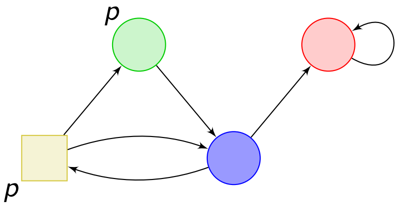

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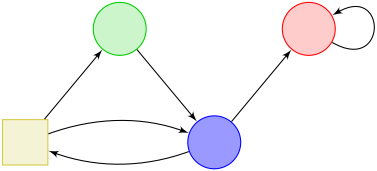
$\langle\!\langle A \rangle\!\rangle\, \varphi$ expresses that A has a strategy to enforce φ.

Theorem

ATL model checking is PTIME*-complete.*
ATL symbolic model checking is EXPTIME*-complete.*

Another semantics: ATL with strategy contexts



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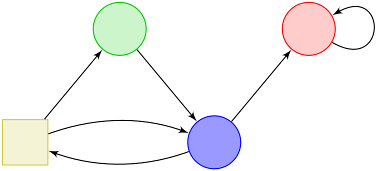

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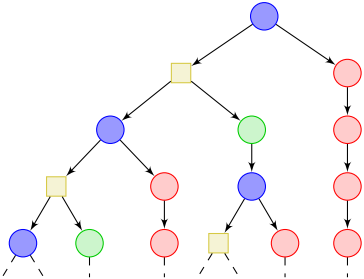

- consider the following strategy of Player $\bigcirc$: “always go to $\square$”;

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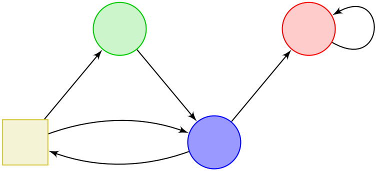
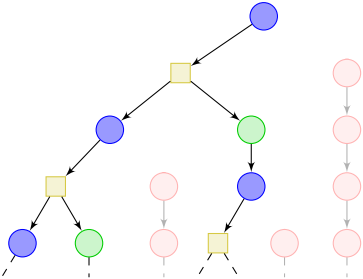


$\langle\!\langle \bigcirc \rangle\!\rangle\ \mathbf{G}(\ \langle\!\langle \Box \rangle\!\rangle\ \mathbf{F}\ \bigcirc)$



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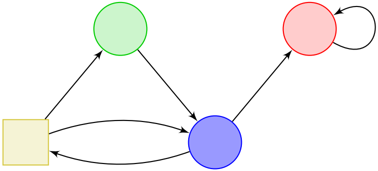

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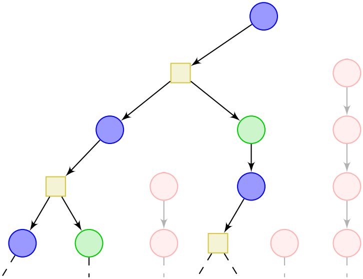

- consider the following strategy of Player ○: "always go to □";
- in the remaining tree, Player □ can always enforce a visit to ○.

ATL with strategy contexts

Definition

ATL$_{sc}$ has two new strategy quantifiers: $\langle\cdot A\cdot\rangle\, \varphi$ and $\rangle\!\!\!\!\;\langle A \rangle\!\!\!\!\;\langle\, \varphi$.

- $\langle\cdot A\cdot\rangle$ is similar to $\langle\!\langle A\rangle\!\rangle$ but assigns the corresponding strategy to A for evaluating φ;
- $\rangle\!\!\!\!\;\langle A \rangle\!\!\!\!\;\langle$ drops the assigned strategies for A.

ATL with strategy contexts

Theorem

ATL_{sc} is strictly more expressive than ATL.

ATL with strategy contexts

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ATL_{sc} is strictly more expressive than ATL.

Proof

$$\langle\!\langle A \rangle\!\rangle\, \varphi \equiv \;\wr\mathrm{Agt}\wr\; \langle\cdot A \cdot\rangle\, \hat{\varphi}$$

ATL with strategy contexts

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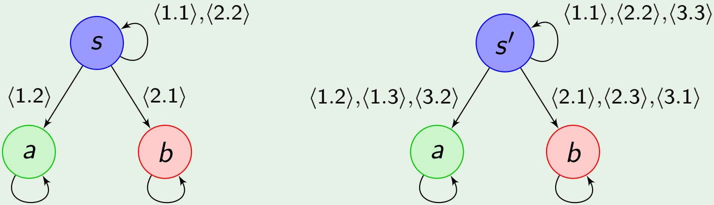
ATL_{sc} is strictly more expressive than ATL.

Proof

$\langle\!\cdot 1 \cdot\!\rangle\,(\langle\!\cdot 2 \cdot\!\rangle\ \mathbf{X}\ a \wedge \langle\!\cdot 2 \cdot\!\rangle\ \mathbf{X}\ b)$ is only true in the second game.
But ATL cannot distinguish between these two games.



What ATL_{sc} can express

- All ATL^* properties;

What ATL_{sc} can express

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- Client-server interactions for accessing a shared resource:

$$\langle\cdot\text{Server}\cdot\rangle\ \mathbf{G}\left[\begin{array}{ll} & \bigwedge_{c\in\text{Clients}} \langle\cdot c\cdot\rangle\ \mathbf{F}\,\text{access}_c \\ \wedge & \\ & \neg \bigwedge_{c\neq c'} \text{access}_c \wedge \text{access}_{c'} \end{array}\right]$$

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- Existence of Nash equilibria:

$$\langle\cdot A_1, \ldots, A_n\cdot\rangle \bigwedge_i \left(\langle\cdot A_i\cdot\rangle\, \varphi_{A_i} \Rightarrow \varphi_{A_i} \right)$$

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- Existence of dominating strategy:

$$\langle\!\cdot A \cdot\!\rangle\ [\!\cdot B \cdot\!]\, (\neg \varphi \Rightarrow [\!\cdot A \cdot\!]\, \neg \varphi)$$

Model checking ATL_{sc}

Theorem

Given a CGS $\mathcal{C}$, a state ℓ_0 and an ATL_{sc} formula φ, we can build an alternating parity tree automaton $\mathcal{A}$ s.t.

$$\mathcal{L}(\mathcal{A}) \neq \varnothing \quad \Leftrightarrow \quad \mathcal{C}, \ell_0 \models_{\varnothing} \varphi.$$

$\mathcal{A}$ has size d-exponential, where d is the maximal number of nested quantifiers.

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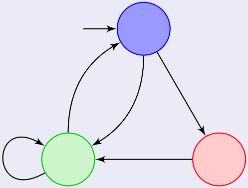
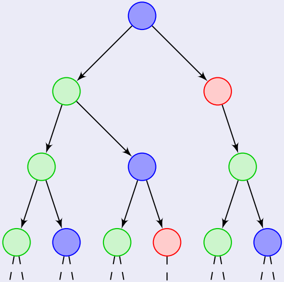
Theorem

Model checking ATL_{sc} is d-EXPTIME*-complete.*

Model checking ATL$_{sc}$

Tree-automata approach





Model checking ATL$_{sc}$

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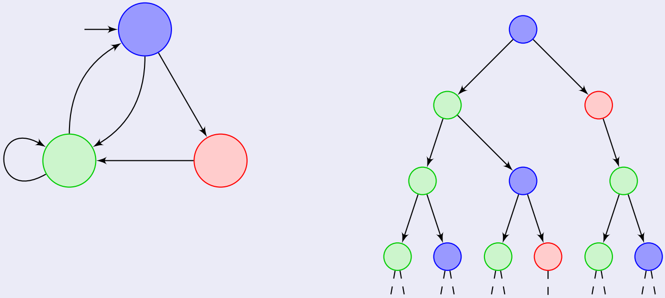

- The unwinding tree is accepted by a deterministic tree automaton;

Model checking ATL$_{sc}$

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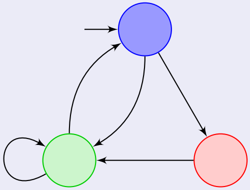

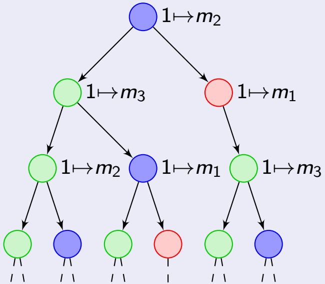

- A strategy is encoded as a labelling of the unwinding tree;

Model checking ATL$_{sc}$

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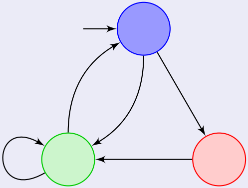

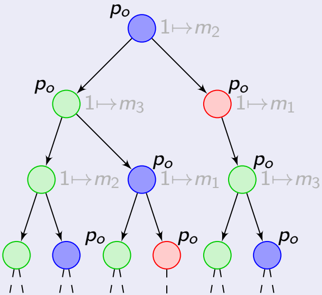

- We can mark outcomes corresponding to selected strategies;

Model checking ATL$_{sc}$

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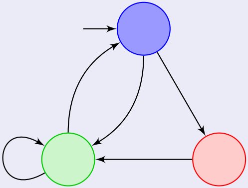

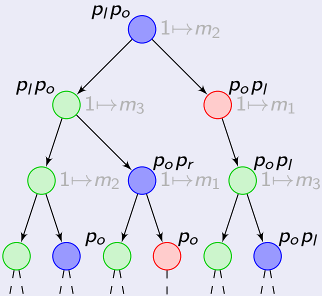

- We mark the tree with extra propositions p_l and p_r, and require that it satisfies $\mathbf{A}(\mathbf{G}\, p_o \Rightarrow p_l \;\mathbf{U}\; p_r)$;

Model checking ATL$_{sc}$

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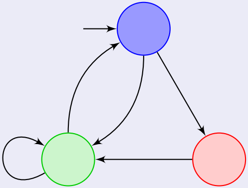
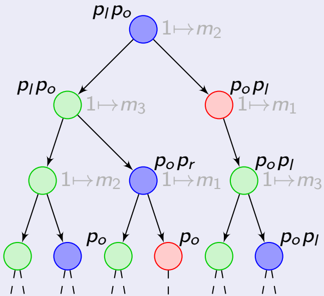
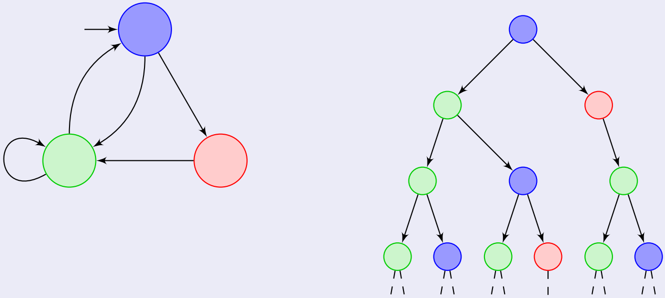




- We require that subtrees rooted at a p_l or p_r node is accepted by the automaton for φ or φ', respectively;

Model checking ATL$_{sc}$

Tree-automata approach



- We can build a tree automaton accepting all trees that *can be labelled* with correct strategies. This requires turning the alternating tree automaton into a non-deterministic one, which yields an exponential-size automaton.

Conclusions

- Our results on ATL_{sc}:
  - ATL_{sc} is a natural semantic extension of the popular ATL;
  - ATL_{sc} is much more expressive: equilibria, client-server interactions... Well-suited for non-zero-sum objectives;
  - There is a price for this expressiveness: high complexity of the model-checking algorithm.

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- Future works:
  - study satisfiability of ATL_{sc};
  - behavioural equivalence for ATL_{sc}.
  - handle stochastic strategies, partial observation, ...