Some Approaches to Rational Verification in Multiagent Systems

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Outline

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Classical Verification

- Given a system P and formal specification φ

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- *Correctness*: Does the behaviour of P reflect φ?

Rational Verification

- How do we define correctness in multiagent systems?

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Rational Verification

- How do we define correctness in multiagent systems?
- Each agent has her own goal, and the goals are not necessarily aligned
- Unlike classical verification, there is no single "litmus test" for system correctness

Rational Verification

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- Agents pursue their interests strategically

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- Agents pursue their interests strategically
- An appropriate framework for studying strategic interaction between self-interested agents: **game theory**

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- **Nash Equilibrium** (NE) is the most widely-used
- A player moving away from NE will be worse off
- Moving away (from NE) is irrational

Outline

Model Checking

- A system P into a finite state model (*e.g.* Kripke structure)

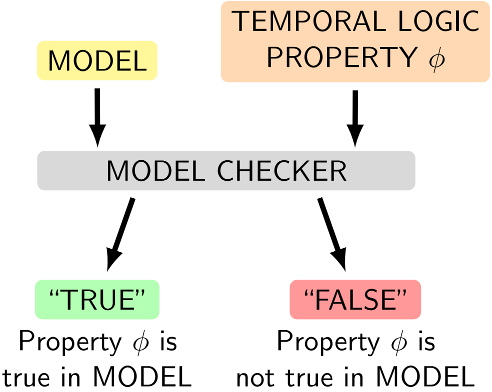

Figure 1: Basic structure of model checking.

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- LTL model checking is more complex (PSPACE-c)
- Symbolic MC with BDDs allows very big number of states
- Active research and development

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  - *interface*: name, list of controlled Boolean variables
  - *guarded commands*: defines choices available at each state

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- $\Phi_i \subseteq \Phi$, set of controlled variables
- I_i is a finite set of **init** guarded commands s.t. $\forall g \in I_i$, $ctr(g) \subseteq \Phi_i$
- U_i is a finite set of **update** guarded commands s.t. $\forall g \in U_i$, $ctr(g) \subseteq \Phi_i$

SRML

module *toggle* **controls** x

init

$:: \top \rightsquigarrow x' := \top;$

$:: \top \rightsquigarrow x' := \bot;$

update

$:: \neg x \rightsquigarrow x' := \top;$

$:: x \rightsquigarrow x' := \bot;$

Figure 2: Example of module toggle in SRML.

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- γ_i in LTL, CTL formula for LTL, CTL RMG, respectively

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- Strategy in LTL RMG is *deterministic*, CTL RMG *non-deterministic*

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- CTL RMG: $\vec{\sigma}$ induces a Kripke structure $K_{\vec{\sigma}}$

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- At each time-step peers either tries to download or upload
- In order for one peer to download successfully, the other must be uploading at the same time
- Both peers are interested in downloading infinitely often

P2PP in RMG

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- $A = (\{a, b\}, \{u_a, u_b, d_a, d_b\}, m_a, m_b)$
- $\gamma_a = \mathbf{GF}(d_a \wedge u_b)$, $\gamma_b = \mathbf{GF}(d_b \wedge u_a)$

P2PP Arena in SRML

module m_a **controls** u_a, d_a	**module** m_b **controls** u_b, d_b
init	**init**
$:: \top \rightsquigarrow u'_a := \top, d'_a := \bot;$	$:: \top \rightsquigarrow u'_b := \top, d'_b := \bot;$
$:: \top \rightsquigarrow u'_a := \bot, d'_a := \top;$	$:: \top \rightsquigarrow u'_b := \bot, d'_b := \top;$
update	**update**
$:: \top \rightsquigarrow u'_a := \top, d'_a := \bot;$	$:: \top \rightsquigarrow u'_b := \top, d'_b := \bot;$
$:: \top \rightsquigarrow u'_a := \bot, d'_a := \top;$	$:: \top \rightsquigarrow u'_b := \bot, d'_b := \top;$

Figure 3: P2PP arena in SRML.

P2PP Structure

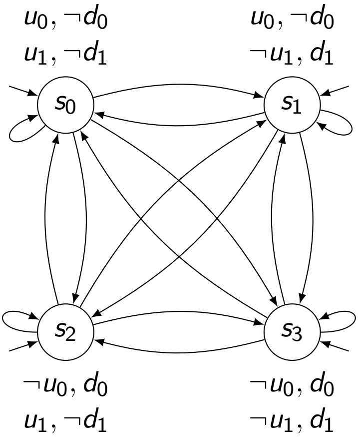

Figure 4: The structure of P2PP arena.

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- Define preference relation $\succsim_i$:

$$\vec{\sigma} \succsim_i \vec{\sigma}' \quad \text{iff} \quad \vec{\sigma}' \models \gamma_i \quad \text{implies} \quad \vec{\sigma} \models \gamma_i.$$

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- A strategy profile $\vec{\sigma}$ is said to be a **Nash equilibrium** of G if for all players i and all strategies $\vec{\sigma}' = (\sigma_1, \ldots, \sigma_{i-1}, \sigma_i', \sigma_{i+1}, \ldots, \sigma_n)$ we have $\vec{\sigma} \succsim_i \vec{\sigma}'$

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- Write $NE(G)$ for the set of pure strategy Nash equilibria

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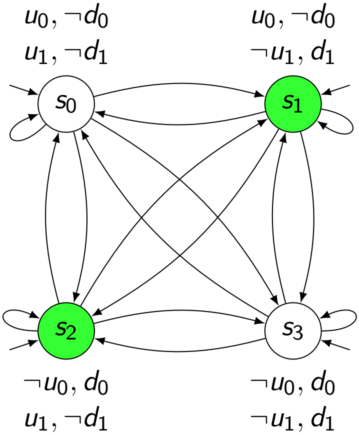
NE-Emptiness

Problem (NE-EMPTINESS)

Given a multiagent system G. Is it the case that $NE(G) \neq \emptyset$?

NE-Emptiness

- Obviously, $NE(G_{P2P}) \neq \emptyset$ is true



NE-Emptiness

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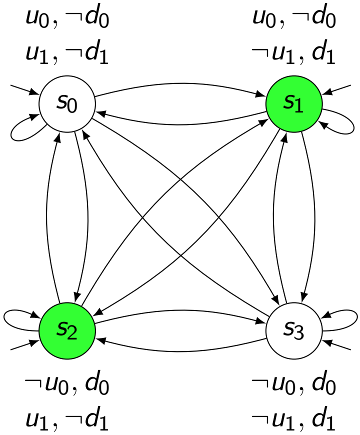
- A run that visits s_1 and s_2 infinitely often



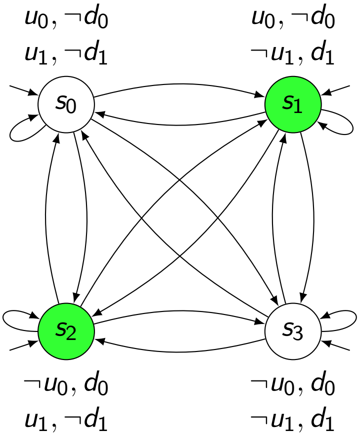
E-Nash

Problem (E-NASH)

Given a multiagent system G and temporal formula φ. Is it the case that $\rho(\vec{\sigma}) \models \varphi$ in any $\vec{\sigma} \in NE(G)$?

E-Nash

- Let $\varphi = \mathbf{GF}(d_a \wedge u_b)$



E-Nash

- Let $\varphi = \mathbf{GF}(d_a \wedge u_b)$
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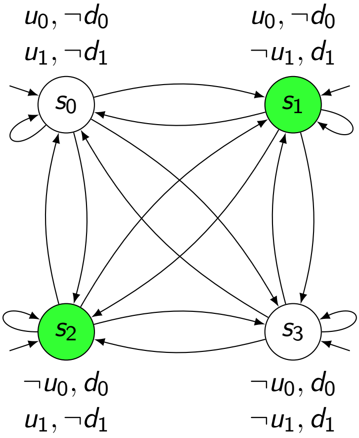

A-Nash

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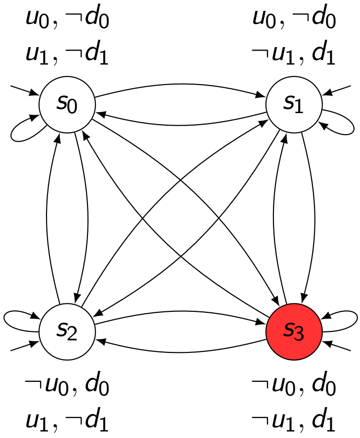

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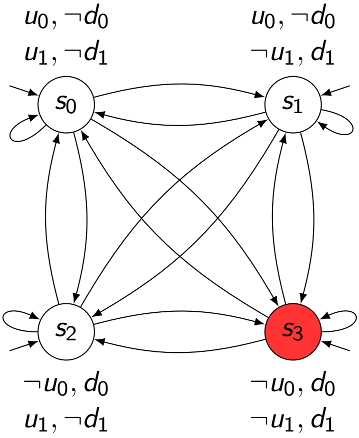

NE-Membership

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Given a multiagent system G and strategy profile $\vec{\sigma}$. Is it the case that $\vec{\sigma} \in NE(G)$?

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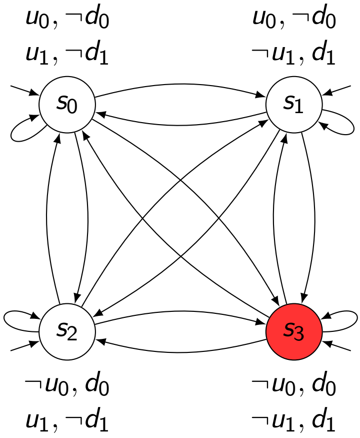

NE-Membership

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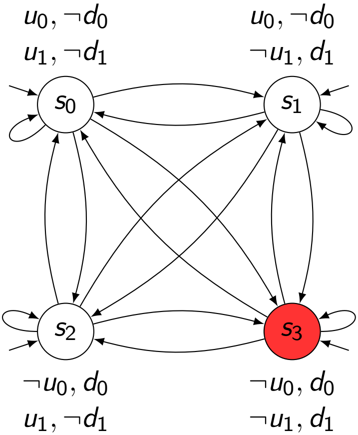
- Then $\vec{\sigma} \in NE(G)$ is true



Outline

Computational Complexity Results

	LTL RMG	CTL RMG
NE-Emptiness	2EXPTIME-c	2EXPTIME-hard
E-Nash	2EXPTIME-c	2EXPTIME-hard
A-Nash	2EXPTIME-c	2EXPTIME-hard
NE-Membership	PSPACE-c	2EXPTIME-c

Table 1: Overview of computational complexity results [Gutierrez et al., 2017]

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- Uses *global* and *local* states to capture epistemic properties
- Latest implementation supports ATL and SL
- SL quite expressive, possible to reason about NE

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- Has been around for more than 10 years

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- Particularly solves NE-MEMBERSHIP
- Accepts CTL as specification language
- Needs two inputs: system (modelled as CTL RMG) $G = (A, \gamma_1, \ldots, \gamma_n)$ and strategy profile $\vec{\sigma} = (\sigma_1, \ldots, \sigma_n)$

EAGLE

EAGLE's basic algorithm:

1. Build $K_{\vec{\sigma}}$

[1] calling a CTL model checker oracle

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EAGLE

EAGLE's basic algorithm:

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2. If $\exists i \in N$ s.t. $(K_{\vec{\sigma}} \not\models \gamma_i)$[1] and $Sat(A_{CTL} \wedge \gamma_i)$[2] returns true, then output "NO"; otherwise "YES"

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EAGLE with BDD CTL SAT

- As reported in [Toumi et al., 2015], CTL SAT subroutine is the bottleneck

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- Can we check CTL SAT symbolically with BDD [Marrero, 2005]?

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EVE

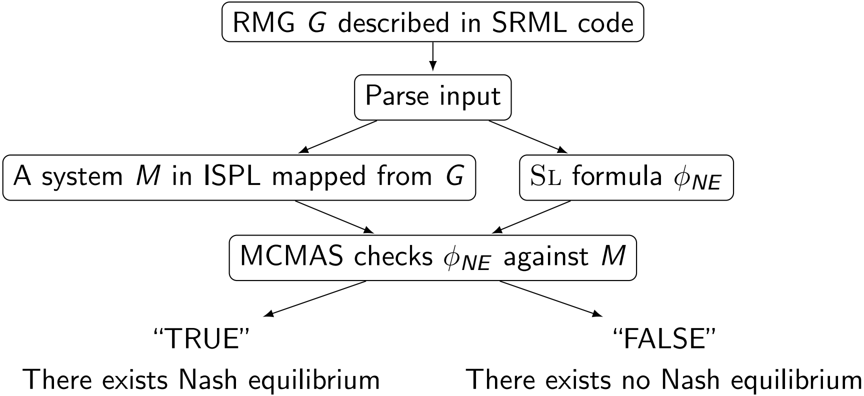

Figure 5: The implementation structure of EVE.

EVE

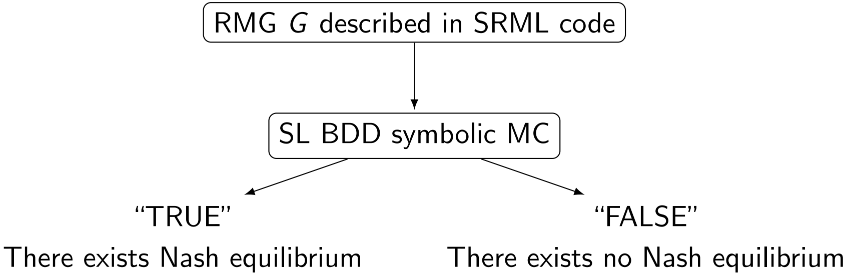

Figure 6: Inject RMG directly into SL BDD symbolic model checker.

Outline

The Punisher(s)

Lemma ([Gutierrez et al., 2015])

ρ is sustained by a Nash equilibrium strategy profile iff every player j whose goal is not satisfied by ρ is punishable at ρ

The Punisher(s)

Nash equilibrium = Punishability + Memory

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Why Parity?

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- Solves the problem of keeping track deviating run
- Finite number of memoryless strategies
- Development of algorithms to solve PG (latest: quasipolynomial ([Calude et al., 2017], best paper award STOC 2017))

Basic Structure[3]

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Matches theoretical bound of 2EXPTIME for LTL RMGs

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- Compute punishing region PUN
- $G_{PAR} \Rrightarrow G^{W}_{PAR}$ from $PUN_{N \setminus W}, W \subseteq N$ (winning coalition)
- If $\exists W$ win in G^{W}_{PAR}, then yes; otherwise no

Matches theoretical bound of 2EXPTIME for LTL RMGs

[3] ongoing joint work: Julian Gutierrez, Giuseppe Perelli, Michael Wooldridge

Demo

- Consider a network composed of 2 clients: $client_a, client_b$ and 2 servers: $server_1, server_2$

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- $server_1$ is an old server, it needs longer rest time

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Demo

- $\gamma_a = \mathbf{G}(r_a \rightarrow \mathbf{X}(s_1 \vee s_2))$

Demo

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Demo

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- $\gamma_2 = \mathbf{GF} \neg s_2$

References I

Calude, C. S., Jain, S., Khoussainov, B., Li, W., and Stephan, F. (2017).
Deciding parity games in quasipolynomial time.
STOC.
To appear.

References II

Gutierrez, J., Harrenstein, P., and Wooldridge, M. (2017).
From model checking to equilibrium checking: Reactive modules for rational verification.
Artif. Intell., 248:123–157.

Lomuscio, A., Qu, H., and Raimondi, F. (2015).
Mcmas: an open-source model checker for the verification of multi-agent systems.
International Journal on Software Tools for Technology Transfer, pages 1–22.

References III

Marrero, W. (2005).
Using bdds to decide CTL.
In *Tools and Algorithms for the Construction and Analysis of Systems, 11th International Conference, TACAS 2005, Held as Part of the Joint European Conferences on Theory and Practice of Software, ETAPS 2005, Edinburgh, UK, April 4-8, 2005, Proceedings*, pages 222–236.

Toumi, A., Gutierrez, J., and Wooldridge, M. (2015).
Theoretical Aspects of Computing - ICTAC 2015: 12th International Colloquium, Cali, Colombia, October 29-31, 2015, Proceedings, chapter A Tool for the Automated Verification of Nash Equilibria in Concurrent Games, pages 583–594.
Springer International Publishing, Cham.