# EFP 2.0: A MULTI-AGENT EPISTEMIC SOLVER WITH MULTIPLE E-STATE REPRESENTATIONS

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**Francesco Fabiano**, Alessandro Burigana,
Agostino Dovier and Enrico Pontelli

**University of Udine** & **New Mexico State University**

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# Overview



1. Multi-Agent Epistemic Planning
2. A New Epistemic State Representation
3. Contribution
4. Conclusions & Future Works

Chapter 1

# Multi-Agent Epistemic Planning

# Introduction



## Epistemic Reasoning

Reasoning not only about agents' perception of the world but also about agents' *knowledge* and/or *beliefs* of her and others' beliefs.

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## Multi-agent Epistemic Planning Problem [BA11]

Finding plans where the goals can refer to:

- the state of the world
- the knowledge and/or the beliefs of the agents

Chapter 2

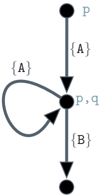
# A New Epistemic State Representation

# Possibilities Overview



- Introduced by Gerbrandy and Groeneveld [GG97]
- Used to represent multi-agent information change
- Based on *non-well-founded sets*
- Corresponds with a class of *bisimilar Kripke structures* [Ger99]

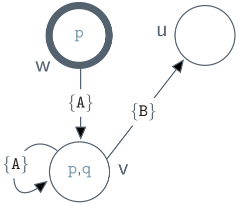
### A possibility




### Its system of equation

$$\begin{cases} w(p) = 1 & w(q) = 0 \\ v(p) = 1 & v(q) = 1 \\ u(p) = 0 & u(q) = 0 \\ w(\mathtt{A}) = \{v\} & w(\mathtt{B}) = \{\emptyset\} \\ v(\mathtt{A}) = \{v\} & v(\mathtt{B}) = \{u\} \\ u(\mathtt{A}) = \{\emptyset\} & u(\mathtt{B}) = \{\emptyset\} \end{cases}$$

### Corresponding K-Structure



# Possibilities Formal Definition



## Possibility [GG97]

Let $\mathcal{AG}$ be a set of agents and $\mathcal{F}$ a set of propositional variables:

- A *possibility* u is a function that assigns to each propositional variable $\ell \in \mathcal{F}$ a truth value $u(\ell) \in \{0, 1\}$ and to each agent $ag \in \mathcal{AG}$ a set of possibilities $u(ag) = \sigma$ (*information state*).

**Intuitively:**

- The possibility u is a possible interpretation of the world and of the agents' beliefs
- $u(\ell)$ specifies the truth value of the literal $\ell$
- $u(ag)$ is the set of all the interpretations the agent ag considers possible in u

# The action language $m\mathcal{A}^\rho$



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- Agents with degrees of awareness w.r.t. actions execution

  **F**ully observant **P**artial observant **O**blivious

Chapter 3

# Contribution

# $m\mathcal{A}^\rho$ updated Semantics



Provided an updated formalization for $m\mathcal{A}^\rho$ transition function:

- Redesigned semantics of $m\mathcal{A}^\rho$ (w.r.t. [Fab+19])
  - More compact and clean
  - More efficient implementation

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- Redesigned semantics of $m\mathcal{A}^\rho$ (w.r.t. [Fab+19])
  - More compact and clean
  - More efficient implementation

- Demonstrated that $m\mathcal{A}^\rho$ respects fundamental properties of multi-agent epistemic reasoning

# The Planner EFP 2.0



- Comprehensive **E**pistemic **F**orward **P**lanner

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  - Kripke structures: follows the semantics of $m\mathcal{A}^*$
  - Possibilities: follows the **new** semantics of $m\mathcal{A}^\rho$

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- Kripke structures size reduction based on Paige and Tarjan's algorithm [PT87]
- Mechanism for *already visited* e-states verification

# Experimental Evaluation I



EFP 1.0 = planner of [Le+18]

K-MAL = EFP 2.0 + K. structures

K-OPT = K-MAL + e-state reduction

P-MAR = EFP 2.0 + possibilities

TO = Time Out (25 minutes)

WP = Wrong Plan

| **CB** with $|\mathcal{AG}| = 3$, $|\mathcal{F}| = 8$, $|\mathcal{A}| = 21$ | | | | |
|---|---|---|---|---|
| *L* | EFP 1.0 | K-MAL | K-OPT | P-MAR |
| 2 | .003 | .003 | .006 | **.001** |
| 3 | .048 | .077 | .097 | **.016** |
| 5 | WP | 5.546 | 1.438 | **.367** |
| 6 | WP | 108.080 | 14.625 | **2.932** |
| 7 | WP | 317.077 | 38.265 | **6.996** |

Coin in the Box domain.

| **AL** with $|\mathcal{AG}| = 2$, $|\mathcal{F}| = 4$, $|\mathcal{A}| = 6$ | | | | |
|---|---|---|---|---|
| *d* | EFP 1.0 | K-MAL | K-OPT | P-MAR |
| 2 | .43 | .32 | .42 | **.07** |
| 4 | .96 | .75 | .64 | **.11** |
| 6 | 26.20 | 27.85 | 13.51 | **2.44** |
| 8 | TO | TO | 883.87 | **150.92** |
| C | .44 | .32 | .43 | **.08** |

Assembly Line.

# Experimental Evaluation II



K-MAL = EFP 2.0 + K. structures

P-MAR = EFP 2.0 + possibilities

K-OPT = K-MAL + e-state reduction

-NV = config w/o visited check

| Grapevine | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $\|\mathcal{AG}\|$ | $\|\mathcal{F}\|$ | $\|\mathcal{A}\|$ | $L$ | K-MAL-NV | K-MAL | K-OPT-NV | K-OPT | P-MAR-NV | P-MAR |
| 3 | 9 | 24 | 2 | .09 | **.09** | **.14** | .15 | .03 | **.02** |
| | | | 4 | 9.19 | **8.13** | 10.20 | **9.95** | 1.34 | **1.25** |
| | | | 5 | 94.49 | **75.32** | 84.07 | **75.87** | 8.67 | **7.71** |
| | | | 6 | 372.64 | **278.93** | 291.62 | **230.69** | 27.63 | **20.26** |
| 4 | 12 | 40 | 2 | 1.85 | **1.786** | **2.33** | 2.34 | **.17** | .18 |
| | | | 4 | 403.11 | **274.53** | 205.00 | **152.07** | 13.49 | **7.31** |
| | | | 5 | TO | TO | TO | **1315.38** | 123.54 | **36.54** |
| | | | 6 | TO | TO | TO | TO | 427.97 | **108.64** |

Runtimes for the Grapevine domain. We compare the configurations with and without (-NV) the visited e-states check.

# Experimental Evaluation III



EFP 1.0 = planner of [Le+18]

P-MAR = EFP 2.0 + possibilities

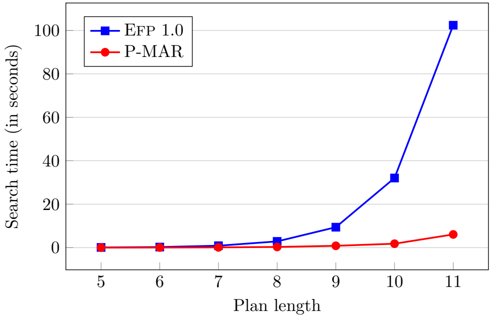


Figure: Comparison between EFP 1.0 and EFP 2.0 on **SC**.

Chapter 4

# Conclusions & Future Works

# Conclusions



EFP 2.0 provided significantly **better results** w.r.t. the previous **state-of-the-art**

- Possibilities as e-state
- Dynamic programming paradigm
- Reduced size of e-states
- Complete refactoring of EFP 1.0:
  - Corrections
  - Optimizations

# Future Works



- E-state symbolic representations
- Concept of *non-consistent belief*
- Formalization of novel concepts such as *trust*, *lies* and *misconception*
- Consider heuristics as in [Le+18]

Thank You
for the attention

# References I


[BA11] Thomas Bolander and Mikkel Birkegaard Andersen. "Epistemic planning for single-and multi-agent systems". In: *Journal of Applied Non-Classical Logics* 21.1 (2011), pp. 9–34. DOI: 10.1016/0010-0277(83)90004-5.

[Bar+15] Chitta Baral et al. "An Action Language for Multi-Agent Domains: Foundations". In: *CoRR* abs/1511.01960 (2015). URL: http://arxiv.org/abs/1511.01960.

# References II

[Fab+19] Francesco Fabiano et al. "Non-well-founded set based multi-agent epistemic action language". In: *Proceedings of the 34th Italian Conference on Computational Logic*. Vol. 2396. CEUR Workshop Proceedings. Trieste, Italy, 2019, pp. 242–259. URL: http://ceur-ws.org/Vol-2396/paper38.pdf.

[Ger99] Jelle Gerbrandy. *Bisimulations on planet Kripke*. Inst. for Logic, Language and Computation, Univ. van Amsterdam, 1999.

[GG97] J. Gerbrandy and W. Groeneveld. "Reasoning about information change". In: *Journal of Logic, Language and Information* 6.2 (1997), pp. 147–169. DOI: 10.1023/A:1008222603071.

# References III

[Le+18] Tiep Le et al. "EFP and PG-EFP: Epistemic Forward Search Planners in Multi-Agent Domains". In: *Proceedings of the Twenty-Eighth International Conference on Automated Planning and Scheduling*. Delft, The Netherlands: AAAI Press, 2018, pp. 161–170. ISBN: 978-1-57735-797-1. URL: https://aaai.org/ocs/index.php/ICAPS/ICAPS18/paper/view/17733.

[PT87] Robert Paige and Robert E Tarjan. "Three partition refinement algorithms". In: *SIAM Journal on Computing* 16.6 (1987), pp. 973–989.