University of Udine
Department of Mathematics, Computer Science and Physics

MODELLING MULTI-AGENT EPISTEMIC PLANNING IN ASP

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Overview

1. Multi-Agent Epistemic Planning
2. Possibilities
3. The action language $m\mathcal{A}^\rho$
4. PLATO
5. Conclusions

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.

Multi-agent Epistemic Planning Problem [BA11]

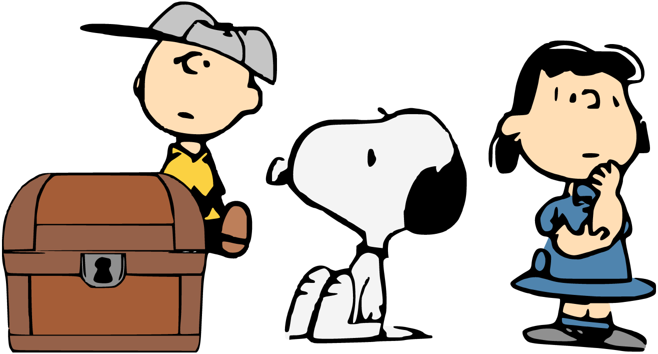
Finding *plans* where the goals can refer to:

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

An Example

Initial State

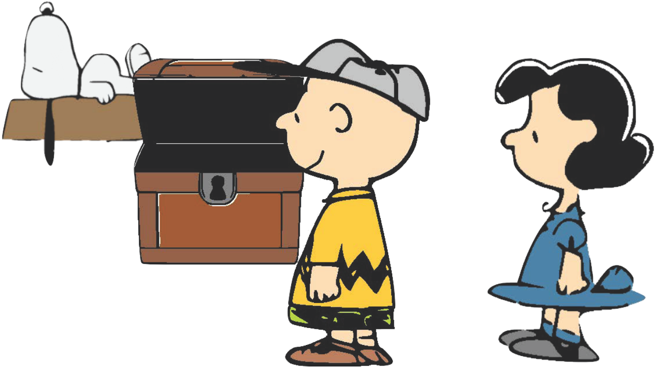
- `Snoopy` and `Charlie` are `looking` while `Lucy` is `¬looking`
- No one knows the `coin position`.



An Example

Goal State

- Charlie knows the coin position
- Lucy knows that Charlie knows the coin position
- Snoopy does not know anything about the plan execution



Notation

Given a set of `agents` $\mathcal{AG}$

Belief formulae

where ag $\in \mathcal{AG}$, $\alpha \subseteq \mathcal{AG}$

We use the operators B_{ag} and C_{α} to model the belief and the common belief of the `agents`.

Properties of B_{ag}

KD45$_n$ and **S5**$_n$ Axioms

Given the fluent formulae ϕ, ψ and the worlds $\mathtt{i}$, $\mathtt{j}$

D $\neg\mathcal{R}_{\mathtt{i}}\bot$ $\mathcal{B}$ $\mathcal{K}$

K $(\mathcal{R}_{\mathtt{i}}\varphi \wedge \mathcal{R}_{\mathtt{i}}(\varphi \implies \psi)) \implies \mathcal{R}_{\mathtt{i}}\psi$ $\mathcal{B}$ $\mathcal{K}$

T $\mathcal{R}_{\mathtt{i}}\varphi \implies \varphi$ $\mathcal{K}$

4 $\mathcal{R}_{\mathtt{i}}\varphi \implies \mathcal{R}_{\mathtt{i}}\mathcal{R}_{\mathtt{i}}\varphi$ $\mathcal{B}$ $\mathcal{K}$

5 $\neg\mathcal{R}_{\mathtt{i}}\varphi \implies \mathcal{R}_{\mathtt{i}}\neg\mathcal{R}_{\mathtt{i}}\varphi$ $\mathcal{B}$ $\mathcal{K}$

Chapter 2

Possibilities

Overview

- Introduced by Gerbrandy and Groeneveld [GG97]
- Used to represent *multi-agent information change*
- Based on *non-well-founded sets*

Formal Definition

Let $\mathcal{AG}$ be a set of agents and $\mathcal{F}$ a set of fluents.

Possibility [GG97]

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

Intuitively a possibility is a possible configuration of the world:

- $\mathsf{u}(\mathtt{f})$ specifies the truth value of the fluent $\mathtt{f}$ (plays the role of the valuation function)
- $\mathsf{u}(\mathtt{ag})$ is the set of all the worlds that agent $\mathtt{ag}$ considers possible in u (plays the role of the accessibility relations)
- Representable with graphs: we will use graph terminology

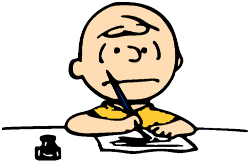
Chapter 3

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

Action types

We introduced the action language $m\mathcal{A}^\rho$ in [Fab+20]

- Used to describe MEP problems
- Uses possibilities as states
- Actions preconditions: belief formulae



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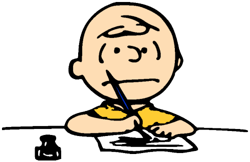
Three types of actions:

- *Ontic*: modifies some fluents of the world

  `Charlie opens the box`



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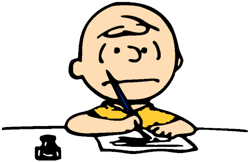
  `Charlie peeks inside the box`



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  Charlie *opens* the box

- Sensing: senses the true value of a fluent

  Charlie *peeks* inside the box

- *Announcement*: announces the fluent to other agents

  `Charlie announces the coin position`

Observability Relations

An *execution* of an action might change or not an agents' belief accordingly to her degree of awareness

Action type	Full observers	Partial Observers	Oblivious
Ontic	✓		✓
Sensing	✓	✓	✓
Announcement	✓	✓	✓

Chapter 4

PLATO

Overview

PLATO, e**P**istemic mu**L**ti-agent **A**nswer se**T** programming s**O**lver:

- Declarative encoding in `ASP` of MEP
- Based on the language $m\mathcal{A}^\rho$
- Main components: *initial state generation*, *entailment*, *transition function*
- Exploits *clingo*'s multi-shot capabilities [Geb+19]
- Formal proof of correctness

Encoding possibilities

Let u be a possibility.

ASP encoding: possibilities

We encode u with the atom possible_world(T_u, R_u, P_u), where:

- T_u tells us when u was created
- R_u is the *repetition* of u
- P_u is the numerical index of u

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ASP encoding: pointed possibility

If u is the possibility that represents the *real configuration* of the world, we encode it with the atom pointed(T_u, R_u, P_u).

When the context is clear we will use *only* P_u instead of (T_u, R_u, P_u).

Encoding possibilities

Let u, v be two possibilities, let AG be an agent and let F be a fluent.

ASP encoding: information states

We encode $v \in u(\mathtt{AG})$ with the atom $\mathtt{believes}(\mathtt{P_u}, \mathtt{P_v}, \mathtt{AG})$.

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ASP encoding: interpretations

We encode $u(\mathtt{F}) = 1$ with the atom $\mathtt{holds}(\mathtt{P_u}, \mathtt{F})$.

Entailment

Given a possibility P and a belief formula F.

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```
entails (P,            F)  :- holds(P,F), fluent(F).
entails (P,       neg(F))  :- not entails(P,F).
entails (P,  and(F1,F2))   :- entails(P,F1), entails(P,F2).
entails (P,   or(F1,F2))   :- entails(P,F1).
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not_entails  (P1,     b(AG,F))  :- not entails(P2,F), believes(P1,P2,AG).
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not_entails  (P1,    c(AGS,F))   :- not entails(P2,F), reaches(P1,P2,AGS).
entails      (P,     c(AGS,F))   :- not not_entails(P,c(AGS,F)).
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Ontic actions

Let *open* be an ontic action such that

- It sets the fluent `opened` to true
- Only `Charlie` and `Lucy` are attentive

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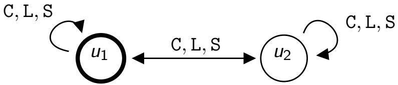

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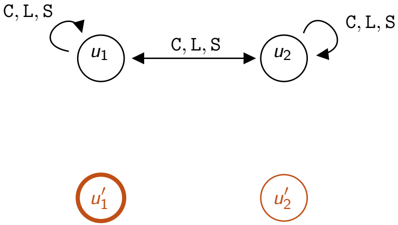
Ontic actions

Let *open* be an ontic action such that

- It sets the fluent opened to true
- Only Charlie and Lucy are attentive

$$\mathtt{pw}(\mathtt{u}'_\mathtt{i})\ \mathtt{:-}\ \mathtt{pointed}(\mathtt{u}_1), \mathtt{reaches}(\mathtt{u}_1, \mathtt{u}_\mathtt{i}, \mathtt{AGS}), \mathtt{fully\_obs}(\mathtt{AGS}). \quad (i \in \{1,2\})$$



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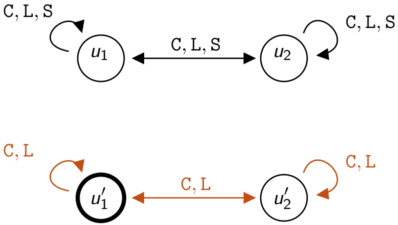

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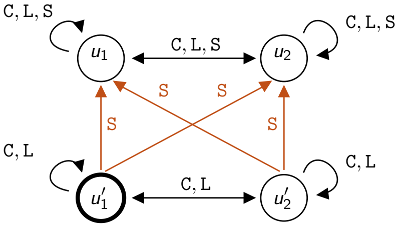

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Sensing/Announcement actions

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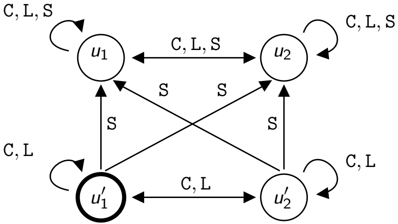

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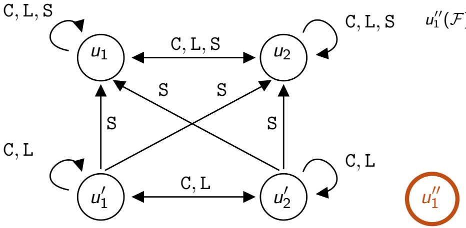

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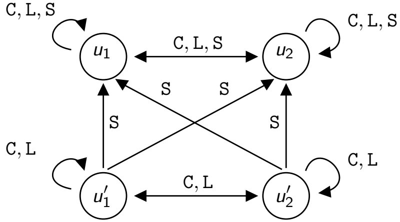
$$\mathtt{pw}(\mathtt{u}_2'') \;\mathtt{:-}\; \mathtt{pointed}(\mathtt{u}_1'), \mathtt{reaches}(\mathtt{u}_1', \mathtt{u}_2', \mathtt{AGS}), \mathtt{not\_oblivious}(\mathtt{AGS}).$$



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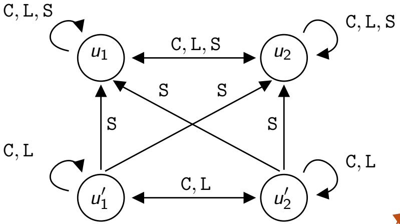
$$\mathtt{holds\_sensed}(\mathtt{u_i}, \mathtt{peek}) = \mathtt{holds\_sensed}(\mathtt{u_j}, \mathtt{peek}).$$



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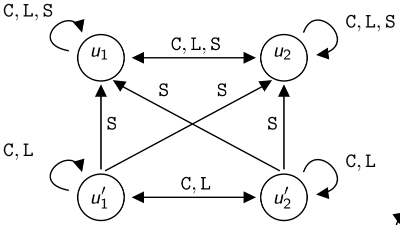

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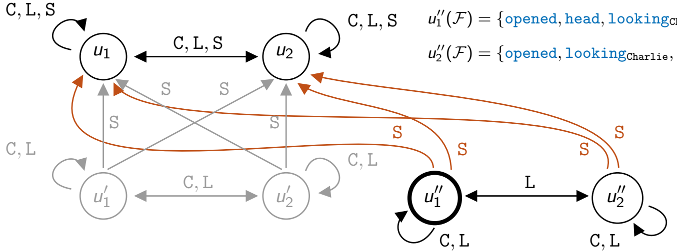

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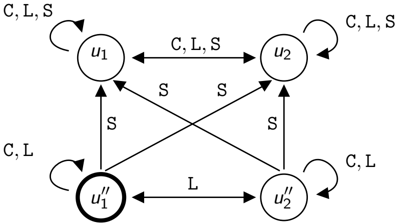

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Correctness w.r.t. $m\mathcal{A}^\rho$

Let u, v be two possibilities and ψ be a belief formula.

Entailment correctness

For each u, we have that $\forall\ \psi \quad \mathsf{u} \models_\Phi \psi \quad \text{iff } \mathsf{u} \models_\Gamma \psi$.

Initial state generation correctness

For each u, v such that u is the initial state in $m\mathcal{A}^\rho$ and v is the initial state in PLATO then $\forall\ \psi \quad \mathsf{u} \models_\Phi \psi \quad \text{iff } \mathsf{v} \models_\Gamma \psi$.

Transition function correctness

Let a be an action instance. For each u, v such that $\forall\ \psi \quad \mathsf{u} \models_\Phi \psi$ iff $\mathsf{v} \models_\Gamma \psi$, then $\forall\ \psi \quad \Phi(\mathsf{a}, \mathsf{u}) \models_\Phi \psi \quad \text{iff } \Gamma(\mathsf{a}, \mathsf{v}) \models_\Gamma \psi$.

Experimental evaluation

SC: $\lvert\mathcal{AG}\rvert = 9$, $\lvert\mathcal{F}\rvert = 12$, $\lvert\mathcal{A}\rvert = 14$				
L	`many`	`frumpy`	K-BIS	P-MAR
4	.24	.24	.03	**.007**
6	2.56	2.49	.16	**.04**
8	36.79	38.34	4.23	**.30**
9	204.52	146.343	5.79	**.83**
10	`TO`	839.27	7.36	**1.78**

Gr: $\lvert\mathcal{AG}\rvert = 3$, $\lvert\mathcal{F}\rvert = 9$, $\lvert\mathcal{A}\rvert = 24$				
L	Total	Ground	Solve	Atoms
3	.97	.60	.36	28'615
4	4.25	2.24	2.01	42'022
5	32.83	2.52	30.31	71'482
6	211.69	5.27	206.41	140'305
7	1066.80	16.94	1049.86	302'623

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	CC_1: $\|\mathcal{AG}\| = 2$, $\|\mathcal{F}\| = 10$, $\|\mathcal{A}\| = 16$				**CC_2**: $\|\mathcal{AG}\| = 3$, $\|\mathcal{F}\| = 13$, $\|\mathcal{A}\| = 24$			
L	`single`	`multi`	K-BIS	P-MAR	`single`	`multi`	K-BIS	P-MAR
3	48.74	6.52	.08	**.02**	153.76	14.07	.13	**.03**
4	188.32	8.74	.16	**.03**	`TO`	28.02	.54	**.10**
5	`TO`	7.68	1.14	**.16**	`TO`	16.13	4.89	**.60**
6	1222.67	10.83	4.42	**0.64**	`TO`	14.84	12.66	**1.71**
7	`TO`	30.08	16.06	**2.61**	`TO`	56.48	142.06	**12.37**

Chapter 5

Conclusions

Conclusions

- Exploited a *declarative* approach to implement Multi-Agent Epistemic Planning
- Improved readability and code maintenance
- Straightforward semantical adaptations
- Results comparable to the imperative approach
- Formal *proof* of correctness

Future works

- Enhancement of the entailment rules ($\checkmark$)
- Formal proof of equivalence between $m\mathcal{A}^*$ and $m\mathcal{A}^\rho$ ($\checkmark$)
- Bringing DELPHIC into PLATO ($\circlearrowleft$)
- We are using PLATO to implement novel concepts in MEP, such as *trust*, *lies* and *misconceptions*

The end

Thank You
for the attention

References I

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[Fab+20] Francesco Fabiano et al. "EFP 2.0: A Multi-Agent Epistemic Solver with Multiple E-State Representations". In: *Proceedings of the Thirtieth International Conference on Automated Planning and Scheduling, Nancy, France, October 26-30, 2020*. AAAI Press, 2020, pp. 101–109. URL: https://aaai.org/ojs/index.php/ICAPS/article/view/6650.

References II

[Geb+19] Martin Gebser et al. "Multi-shot ASP solving with clingo". In: *Theory and Practice of Logic Programming* 19 (2019), pp. 27–82. DOI: 10.1017/S1471068418000054.

[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.

[Son+14] Tran Cao Son et al. "Finitary S5-theories". In: *European Workshop on Logics in Artificial Intelligence*. Springer. 2014, pp. 239–252.

Domains I

- *Assembly Line* (**AL**): two agents are responsible for processing a different part of a product. They can fail in processing their part and inform the other of the status of her task. The agents decide to *assemble* the product or *restart*. Goal: the agents must assemble the product. We change the *depth* of the belief formulae.
- *Coin in the Box* (**CB**). $n \geq 3$ agents are in a room. There is a closed box containing a coin. None of the agents know the coin position. One agent has the key. An agent may look inside the box to sense the state of the coin and also share the result.

Domains II

- *Collaboration and Communication* (**CC**). $n \geq 2$ agents move along a corridor with $k \geq 2$ rooms in which $m \geq 1$ boxes can be located. Agents can determine if a certain box is in the room they are in. They can communicate information about the boxes' position. Agents may move only to adjacent rooms.
- *Grapevine*. $n \geq 2$ agents are located in $k \geq 2$ rooms. Each agent ag knows a "secret" (`s_ag`). Agents can move to an adjacent room and share their secret within the same room.
- *Selective Communication* (**SC**). $n \geq 2$ agents within one of the $k \geq 2$ rooms in a corridor. Agents can move to an adjacent room. In only one of the rooms, agents may acquire some information `q` and may communicate it to others.

Finitary S5 Theories

Finitary **S5**-theory [Son+14]

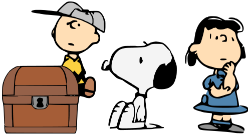
Let ϕ be a fluent formula and let $\mathsf{i} \in \mathcal{AG}$ be an agent. A *finitary S5-theory* is a collection of formulae of the form:

$$(i)\ \phi \quad (ii)\ C\ \phi \quad (iii)\ C\ (B_{\mathsf{i}}\phi \lor B_{\mathsf{i}}\neg\phi) \quad (iv)\ C\ (\neg B_{\mathsf{i}}\phi \land \neg B_{\mathsf{i}}\neg\phi)$$

Each fluent $\mathsf{f} \in \mathcal{F}$ must appear in at least one of the formulae (*ii*)–(*iv*) (for at least one agent $\mathsf{i} \in \mathcal{AG}$).

A finitary **S5**-theory has *finitely many* S5-models up to equivalence.

Initial state generation



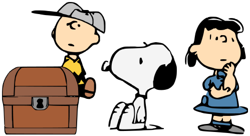
Given

- $\mathcal{AG} = \{\texttt{Snoopy}, \texttt{Charlie}, \texttt{Lucy}\}$
- $\mathcal{F} \quad = \{\texttt{opened}, \texttt{head}, \texttt{looking}_{\texttt{ag}}\}$ $\texttt{ag} \in \mathcal{AG}$

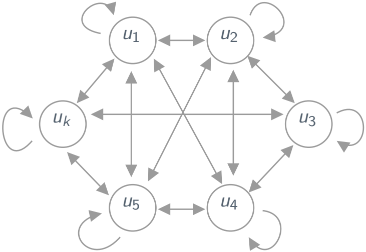
Initial state generation

Given

- $\mathcal{AG} = \{\texttt{Snoopy}, \texttt{Charlie}, \texttt{Lucy}\}$
- $\mathcal{F} = \{\texttt{opened}, \texttt{head}, \texttt{looking}_{\texttt{ag}}\}$ $\texttt{ag} \in \mathcal{AG}$

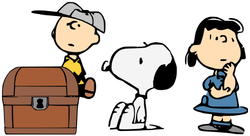


Consider a formula of a finitary **S5** theory.



Formula type:

Initial state generation



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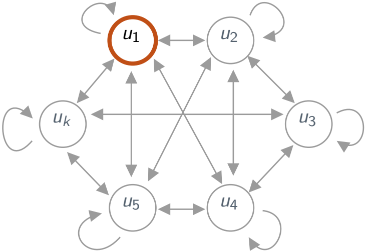
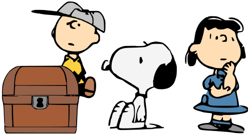


Formula type:

(i) ϕ

Initial state generation



Given

- $\mathcal{AG} = \{\texttt{Snoopy}, \texttt{Charlie}, \texttt{Lucy}\}$
- $\mathcal{F} \quad = \{\texttt{opened}, \texttt{head}, \texttt{looking}_{\texttt{ag}}\}$ $\texttt{ag} \in \mathcal{AG}$

Consider a formula of a finitary **S5** theory.

$u_1(\mathcal{F}) = \{\texttt{head}, \texttt{looking}_{\texttt{Charlie}}, \texttt{looking}_{\texttt{Lucy}}\}$

$u_2(\mathcal{F}) = \{\texttt{looking}_{\texttt{Charlie}}, \texttt{looking}_{\texttt{Lucy}}\}$

Formula type:

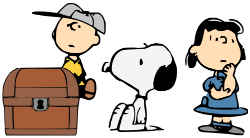
(i) ϕ

(ii) $C\ \phi$

Initial state generation

Given

- $\mathcal{AG} = \{\texttt{Snoopy}, \texttt{Charlie}, \texttt{Lucy}\}$
- $\mathcal{F} = \{\texttt{opened}, \texttt{head}, \texttt{looking}_{\texttt{ag}}\}$ $\texttt{ag} \in \mathcal{AG}$



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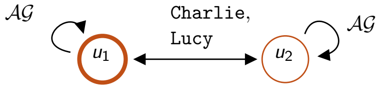


$u_1(\mathcal{F}) = \{\texttt{head}, \texttt{looking}_{\texttt{Charlie}}, \texttt{looking}_{\texttt{Lucy}}\}$

$u_2(\mathcal{F}) = \{\texttt{looking}_{\texttt{Charlie}}, \texttt{looking}_{\texttt{Lucy}}\}$

Formula type:

(i) ϕ

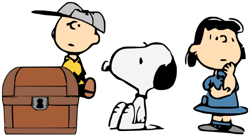
(ii) $C\ \phi$

(iii) $C\ (B_{\mathsf{i}}\phi \vee B_{\mathsf{i}}\neg\phi)$

Formula:

$C\ (B_{\texttt{Lucy}}\texttt{head} \vee B_{\texttt{Lucy}}\neg\texttt{head})$

Initial state generation



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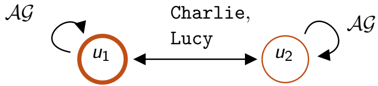


$u_1(\mathcal{F}) = \{\texttt{head}, \texttt{looking}_{\texttt{Charlie}}, \texttt{looking}_{\texttt{Lucy}}\}$

$u_2(\mathcal{F}) = \{\texttt{looking}_{\texttt{Charlie}}, \texttt{looking}_{\texttt{Lucy}}\}$

Formula type:

(i) ϕ

(ii) $C\ \phi$

(iii) $C\ (B_{\text{i}}\phi \lor B_{\text{i}}\neg\phi)$

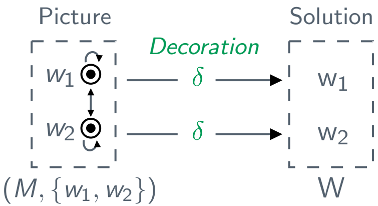
(iv) $C\ (\neg B_{\text{i}}\phi \land \neg B_{\text{i}}\neg\phi)$

From Possibilities to Kripke Models

Definition (Decoration of a Kripke Model)

The *decoration* of a Kripke model $M = (W, R, V)$ is a function δ that, for each $w \in W$, it assigns a possibility $\mathrm{w} = \delta(w)$ such that:

- $\mathrm{w}(\mathtt{f}) = 1$ iff $w \in V(\mathtt{f})$ for each $\mathtt{f} \in \mathcal{F}$, and
- $\mathrm{w}(\mathtt{i}) = \{\delta(w') \mid wR_{\mathtt{i}}w'\}$ for each $\mathtt{i} \in \mathcal{AG}$.



From Possibilities to Kripke Models

Definition (Picture and Solution)

If δ is a decoration of $M = (W, R, V)$ and $W_d \subseteq W$, then:

- (M, W_d) is a *picture* of the possibility spectrum $\mathsf{W} = \{\delta(w) \mid w \in W_d\}$, and
- W is said to be the *solution* of (M, W_d).