University of Udine
Department of Mathematics, Computer Science and Physics

NON-WELL-FOUNDED SET BASED MULTI-AGENT EPISTEMIC ACTION LANGUAGE

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Overview

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

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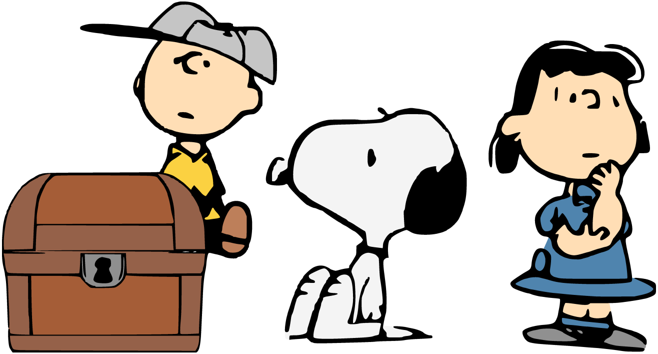
Multi-agent Epistemic Planning Problem **bolander2011epistemic**

Finding *plans* where the goals can refer to:

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

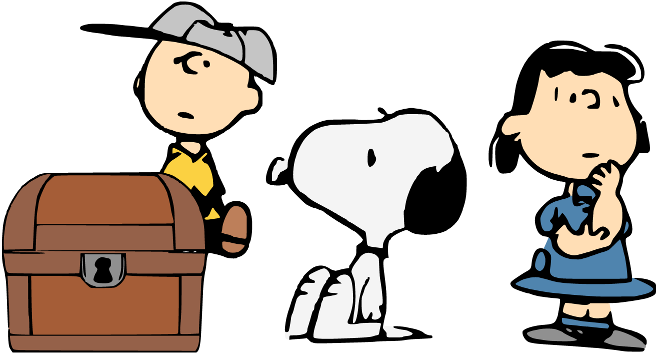
An Example



An Example

Initial State

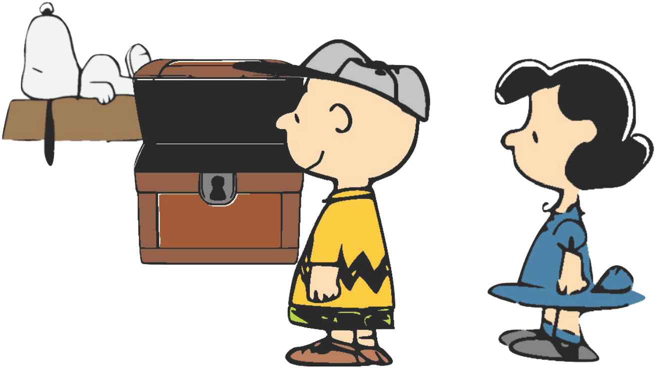
- Snoopy and Charlie are looking while Lucy is $\neg$looking
- No one knows the coin position.



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



Challenges

An `agent` has to reason about his actions effects on

- The *state of the world*
- The `agents`' awareness of the environment
- The `agents`' awareness of other `agents`' *actions*
- The knowledge of other `agents` about his own

Notations

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

Modal operator $\mathbf{B}_{\mathsf{ag}}$ where ag $\in \mathcal{AG}$

Models the beliefs of `ag` about the `state of the world` and/or about the beliefs of other `agents`.

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Expresses the *common belief* of a group of `agents`.

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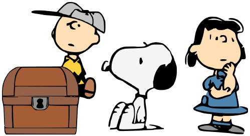
Belief Formulae

Take into consideration *fluents* and/or `agents`' beliefs.

Example of Belief Formulae

Given

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



$\mathbf{B}_{\texttt{Snoopy}}\mathbf{B}_{\texttt{Charlie}}\neg\texttt{opened}$

$\texttt{Snoopy}$ believes that $\texttt{Charlie}$ believes that the box is $\neg\texttt{opened}$.

Example of Belief Formulae

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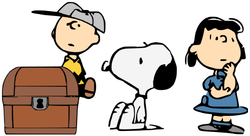


$\mathbf{B}_{\texttt{Snoopy}}\mathbf{B}_{\texttt{Charlie}}\neg\texttt{opened}$

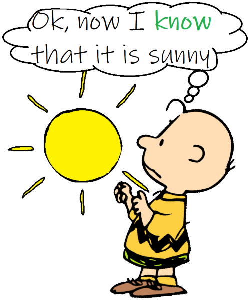
Snoopy believes that Charlie believes that the box is $\neg$opened.

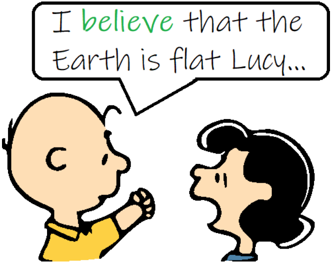
$\mathbf{C}_{\alpha}(\neg\mathbf{B}_{\texttt{Lucy}}\texttt{heads} \wedge \neg\mathbf{B}_{\texttt{Lucy}}\neg\texttt{head})$ where $\alpha = \mathcal{AG}$

It is common knowledge that Lucy does not know whether the coin lies heads or tails up

Knowledge vs. Belief

- The modal operator $\mathbf{B}_{ag}$ represents the worlds' relation
- Different relation's properties imply different meaning for $\mathbf{B}_{ag}$





Knowledge vs. Belief

- The modal operator $\mathbf{B}_{\mathrm{ag}}$ represents the worlds' relation
- Different relation's properties imply different meaning for $\mathbf{B}_{\mathrm{ag}}$
- $\mathcal{K}$*nowledge* and $\mathcal{B}$*elief* are characterized by a subset of the following axioms

Serial (**D**) and S5 (**K,T,4,5**) 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	$(\mathcal{R}_{\mathtt{i}}\varphi \wedge \mathcal{R}_{\mathtt{i}}(\varphi \Rightarrow \psi)) \Rightarrow \mathcal{R}_{\mathtt{i}}\psi$	$\mathcal{B}$ $\mathcal{K}$
T	$\mathcal{R}_{\mathtt{i}}\varphi \Rightarrow \varphi$	$\mathcal{K}$
4	$\mathcal{R}_{\mathtt{i}}\varphi \Rightarrow \mathcal{R}_{\mathtt{i}}\mathcal{R}_{\mathtt{i}}\varphi$	$\mathcal{B}$ $\mathcal{K}$
5	$\neg\mathcal{R}_{\mathtt{i}}\varphi \Rightarrow \mathcal{R}_{\mathtt{i}}\neg\mathcal{R}_{\mathtt{i}}\varphi$	$\mathcal{B}$ $\mathcal{K}$

Chapter 2

Kripke Structures

Description

Pointed Kripke structure

A *Pointed Kripke structure* is a pair $(\langle S, \pi, \mathcal{R}_1, ..., \mathcal{R}_n \rangle, s_0)$, s.t.:

- S is a set of *worlds* and $s_0 \in S$
- $\pi : S \mapsto 2^{\mathcal{F}}$ associates an *interpretation* to each element of S
- for $1 \leq i \leq n$, $\mathcal{R}_i \subseteq S \times S$ is a binary relation over S

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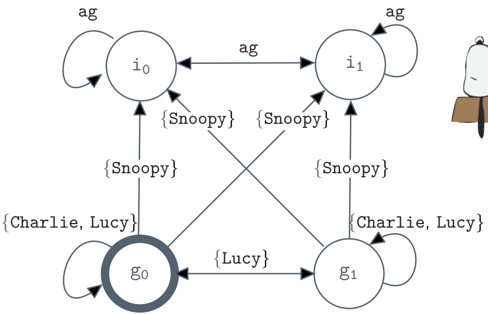
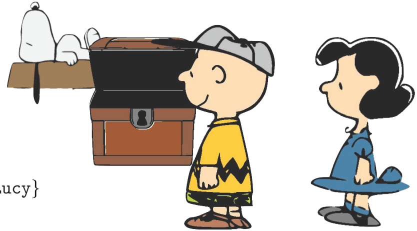


ag = {Charlie, Lucy, Snoopy}



Entailment

Let φ be a belief formula and (M, s) be a pointed Kripke structure:

Entailment w.r.t. a pointed Kripke structure

- $(M, s) \models \varphi$ if φ is a *fluent formula* and $\pi(s) \models \varphi$;

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- $(M, \mathsf{s}) \models \varphi$ if φ is a *fluent formula* and $\pi(\mathsf{s}) \models \varphi$;
- $(M, \mathsf{s}) \models \mathbf{B}_{\mathtt{ag_i}} \varphi$ if $\forall$ t: $(\mathsf{s}, \mathsf{t}) \in \mathcal{R}_\mathsf{i}$ it holds that $(M, \mathsf{t}) \models \varphi$;

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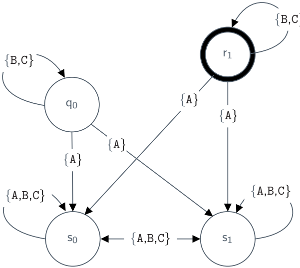
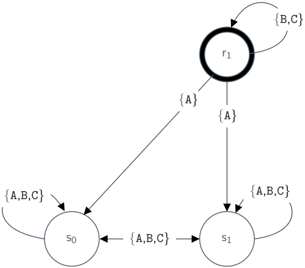
- $(M, s) \models \mathbf{B}_{\mathtt{ag_i}}\varphi$ if $\forall$ t: $(s, t) \in \mathcal{R}_i$ it holds that $(M, t) \models \varphi$;
- $(M, s) \models \mathbf{E}_\alpha\varphi$ if $(M, s) \models \mathbf{B}_{\mathtt{ag_i}}\varphi$ for all $\mathtt{ag_i} \in \alpha$;
- $(M, s) \models \mathbf{C}_\alpha\varphi$ if $(M, s) \models \mathbf{E}^k_\alpha\varphi$ for every $k \geq 0$, where $\mathbf{E}^0_\alpha\varphi = \varphi$ and $\mathbf{E}^{k+1}_\alpha\varphi = \mathbf{E}_\alpha(\mathbf{E}^k_\alpha\varphi)$.

The entailment for the standard operators is defined as usual

Problems

- Solvers require high amount of memory
- In literature the states have been represented explicitly
- State comparison needs to find *bisimilar* states





Solutions

- Heuristics **le2018efp**

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- Symbolic representation of Kripke structures

Solutions

- Heuristics **le2018efp**
- Symbolic representation of Kripke structures
- Alternative representations

Chapter 3

Possibilities

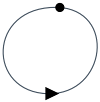
Overview

- Introduced by Gerbrandy and Groeneveld **Gerbrandy1997**
- Used to represent *multi-agent information change*
- Based on *non-well-founded sets*
- Corresponds with a class of bisimilar Kripke structures **gerbrandy1999bisimulations**

Non-well-founded sets

Non-well-founded set Aczel1989-ACZNS-2

A set is *non-well-founded* (or *extraordinary*) when among its descents there are some which are infinite.



The non-well-founded set $\Omega = \{\Omega\}$

Formal Definition

Possibility Gerbrandy1997

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 $\texttt{l} \in \mathcal{F}$ a truth value $\mathrm{u}(\texttt{l}) \in \{0, 1\}$ and to each agent $\texttt{ag} \in \mathcal{AG}$ a set of possibilities $\mathrm{u}(\texttt{ag}) = \sigma$.

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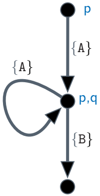
Intuitively ...

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

From Possibilities to Kripke Structures

Considering a possibility

A possibility



From Possibilities to Kripke Structures

Considering a possibility

Can be expressed as a *system of equations*

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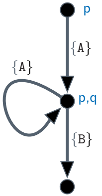

Its system of equation

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

:- gulp!

From Possibilities to Kripke Structures

Considering a possibility

Can be expressed as a *system of equations*

Systems of equations have unique solutions

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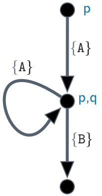

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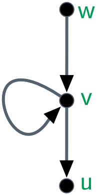
The solution



From Possibilities to Kripke Structures

Considering a possibility

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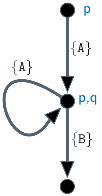
The solution decorates a Kripke structure

A possibility



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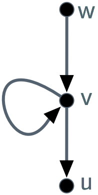
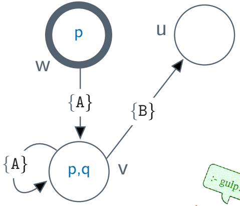


Relative Kripke Structure



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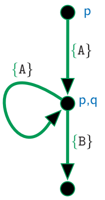

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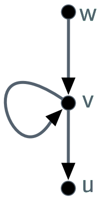

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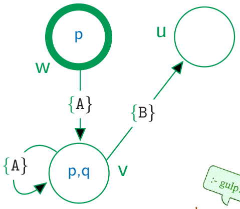


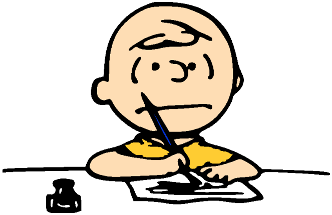
Chapter 4

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

Overview

We introduce the action language $m\mathcal{A}^\rho$

- Used to describe MEP problems
- Same syntax of the action language $m\mathcal{A}+$ **baral2015action**
- As expressive as $m\mathcal{A}+$
- Uses possibilities as states



Actions

Three types of actions:

- *Ontic*: modifies some fluents of the world

    `Charlie` *`opens`* `the box`

Actions

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0.5Ontic: modifies some fluents of the world

- Charlie *opens* the box
- *Sensing*: senses the true value of a fluent

`Charlie peeks inside the box`

Actions

Three types of actions:

0.5Ontic: modifies some fluents of the world

- Charlie *opens* the box

0.5

- 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	✓	✓	✓

Possibility as a state

In $m\mathcal{A}^\rho$ a state is encoded by a possibility where

- $(\texttt{agent}, \sigma)$ represent the possibilities believed by $\texttt{agent}$
- If $\texttt{f} \in \mathcal{F}$ is present then it is true

$$\mathsf{w} = \{(\texttt{ag}, \{\mathsf{w}, \mathsf{w}'\}), (\texttt{C}, \{\mathsf{v}, \mathsf{v}'\}), \texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}, \texttt{heads}\}$$

0.8 where $\texttt{ag} \in \{\texttt{A}, \texttt{B}\}$

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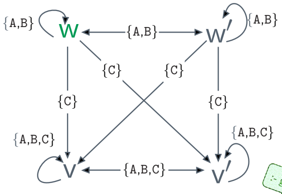
where $\mathtt{ag} \in \{\mathtt{A}, \mathtt{B}\}$.



0.8 Possibility w expanded for clarity

State equality

- Possibilities captures classes of bisimilar Kripke structures
- Possibilities equality considers bisimilarity
- This help for the *visited states* problem in MEP

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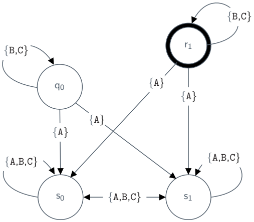
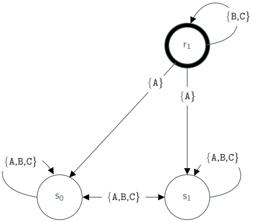
$r_1 = \{(A, \{s_0, s_1\}), (B, \{r_1\}), (C, \{r_1\}), \texttt{look(C)}, \texttt{key(A)}, \texttt{opened}, \texttt{heads}\}$





Entailment

Let $\varphi, \varphi_1, \varphi_2$ be beliefs formula and u be a possibility

Entailment w.r.t. possibilities

- u $\models \mathtt{l}$ if u$(\mathtt{l}) = 1$;

Entailment

Let $\varphi, \varphi_1, \varphi_2$ be beliefs formula and u be a possibility

Entailment w.r.t. possibilities

- u $\models$ 1 if u(1) $= 1$;
- u $\models \mathbf{B}_{\mathrm{ag}}\varphi$ if for each v $\in$ u(ag), v $\models \varphi$;

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The entailment for the standard operators is defined as usual

Ontic Actions

Φ_D for Ontic Actions $\qquad \Phi_D : \mathcal{AI} \times \Sigma \rightarrow \Sigma \cup \{\emptyset\}$

Let a be an *ontic action* instance, u a possibility and `l` be `f` or `¬f`

$$\begin{array}{ll} \Phi_D(\mathrm{a}, \mathrm{u}) = \emptyset & \text{if a is not executable in u} \\ \Phi_D(\mathrm{a}, \mathrm{u}) = \mathrm{v} & \text{if a } \textit{modifies} \text{ the } \texttt{literals} \in \mathrm{caused(a)} \end{array}$$

Where v is

$$\begin{cases} \mathrm{v}(\texttt{l}) = \mathrm{u}(\texttt{l}) & \text{if } \texttt{l} \notin \mathrm{caused(a)} \\ \mathrm{v}(\texttt{l}) = \mathrm{caused(a)}[\texttt{l}] & \text{if } \texttt{l} \in \mathrm{caused(a)} \end{cases}$$

and

$$\begin{cases} \mathrm{v}(\mathbf{ag}) = \mathrm{u}(\mathbf{ag}) & \text{if } \mathbf{ag} \in O_D \\ \mathrm{v}(\mathbf{ag}) = \bigcup_{\mathrm{w} \in \mathrm{u}(\mathbf{ag})} \Phi_D(\mathrm{a}, \mathrm{w}) & \text{if } \mathbf{ag} \in F_D \end{cases}$$

Sensing Actions

Φ_D for Sensing Actions $\Phi_D : \mathcal{AI} \times \Sigma \to \Sigma \cup \{\emptyset\}$

Let a be an *sensing action* instance, and u a possibility and `l` be `f` or `¬f`

$$\Phi_D(\mathsf{a}, \mathsf{u}) = \emptyset \quad \text{if a is not executable in u}$$
$$\Phi_D(\mathsf{a}, \mathsf{u}) = \mathsf{v} \quad \text{if the literal } \mathtt{l} \text{ is } \textit{sensed}$$

Where v is

$$\begin{cases} \emptyset & \text{if } \mathsf{sensed}(\mathsf{a})[\mathtt{l}] \neq \mathsf{u}(\mathtt{l}) \\ \mathsf{v}(\mathsf{ag}) = \mathsf{u}(\mathsf{ag}) & \text{if } \mathsf{ag} \in O_D \\ \mathsf{v}(\mathsf{ag}) = \bigcup_{\mathsf{w} \in \mathsf{u}(\mathsf{ag})} \Phi_D(\mathsf{a}, \mathsf{w}) & \text{if } \mathsf{ag} \in F_D \\ \mathsf{v}(\mathsf{ag}) = \bigcup_{\mathsf{w} \in \mathsf{u}(\mathsf{ag})} (\Phi_D(\mathsf{a}, \mathsf{w}) \cup \Phi_D(\neg\mathsf{a}, \mathsf{w})) & \text{if } \mathsf{ag} \in P_D \end{cases}$$

Announcement Actions

Φ_D for Announcement Actions $\quad \Phi_D : \mathcal{AI} \times \Sigma \rightarrow \Sigma \cup \{\emptyset\}$

Let a be an *announcement action* instance, and u a possibility.

$\Phi_D(\mathrm{a}, \mathrm{u}) = \emptyset$ if a is not executable in u
$\Phi_D(\mathrm{a}, \mathrm{u}) = \mathrm{v}$ if the fluent formula ϕ is *announced*

Where v is

$$
\begin{cases}
\emptyset & \text{if } \mathrm{u} \not\models \phi \\
\mathrm{v}(\mathrm{ag}) = \mathrm{u}(\mathrm{ag}) & \text{if } \mathrm{ag} \in O_D \\
\mathrm{v}(\mathrm{ag}) = \bigcup_{\mathrm{w} \in \mathrm{u}(\mathrm{ag})} \Phi_D(\mathrm{a}, \mathrm{w}) & \text{if } \mathrm{ag} \in F_D \\
\mathrm{v}(\mathrm{ag}) = \bigcup_{\mathrm{w} \in \mathrm{u}(\mathrm{ag})} (\Phi_D(\mathrm{a}, \mathrm{w}) \cup \Phi_D(\neg \mathrm{a}, \mathrm{w})) & \text{if } \mathrm{ag} \in P_D
\end{cases}
$$

Chapter 5

Conclusions

Conclusions

- Exploited an *alternative* to the *Kripke structures* as states representation
- Used *possibilities* to define a stronger concept of states *equality*
- Possibilities helps in *reducing* the search-space dimension
- Defined a new action language for the MEP problem

Future works

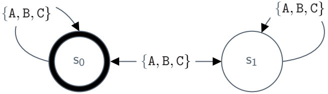
- We started *implementing* a planner for $m\mathcal{A}^\rho$
- Exploit more *set-based operations*: especially for the entailment of group operators
- Formalize the concept of *non-consistent belief* for $m\mathcal{A}^\rho$
- Consider other *alternatives* to Kripke structures, *e.g.*, *OBDD*s

The end

Thank You
for the attention

References I

Side to side Execution



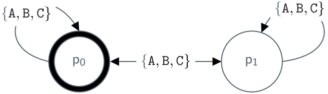
$M_0[\pi](s_0) = \{\texttt{look(ag)}, \texttt{key(A)}, \texttt{heads}\}$
$M_0[\pi](s_1) = \{\texttt{look(ag)}, \texttt{key(A)}\}$

$$\begin{cases} \mathsf{u} & = \{(\mathsf{ag}, \{\mathsf{u}, \mathsf{u}'\}), \\ & \quad \texttt{look(ag)}, \texttt{key(A)}, \texttt{heads}\} \\ \mathsf{u}' & = \{(\mathsf{ag}, \{\mathsf{u}, \mathsf{u}'\}), \\ & \quad \texttt{look(ag)}, \texttt{key(A)}\} \end{cases}$$

where $\texttt{ag} \in \{\texttt{A}, \texttt{B}, \texttt{C}\}$

The initial state

Side to side Execution



$M_1[\pi](p_0) = \{\texttt{look(A)}, \texttt{look(B)}, \texttt{key(A)}, \texttt{heads}\}$

$M_1[\pi](p_1) = \{\texttt{look(A)}, \texttt{look(B)}, \texttt{key(A)}\}$

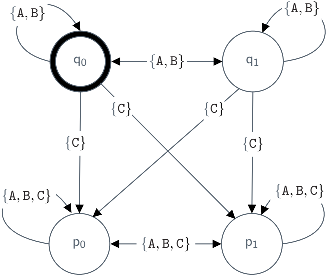
$$\begin{cases} v & = \{(\mathsf{ag}, \{v, v'\}), \texttt{look(A)}, \\ & \quad \texttt{look(B)}, \texttt{key(A)}, \texttt{heads}\} \\ v' & = \{(\mathsf{ag}, \{v, v'\}), \\ & \quad \texttt{look(A)}, \texttt{look(B)}, \texttt{key(A)}\} \end{cases}$$

where $\mathsf{ag} \in \{\texttt{A}, \texttt{B}, \texttt{C}\}$

where $\mathsf{ag} \in \{\texttt{A}, \texttt{B}, \texttt{C}\}$

Execution of $\texttt{distract}(\texttt{C})\langle\texttt{A}\rangle$

Side to side Execution



$M_2[\pi](q_0) = \{\texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}, \texttt{heads}\}$
$M_2[\pi](q_1) = \{\texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}\}$
$M_2[\pi](p_0) = M_1[\pi](p_0)$
$M_2[\pi](p_1) = M_1[\pi](p_1)$

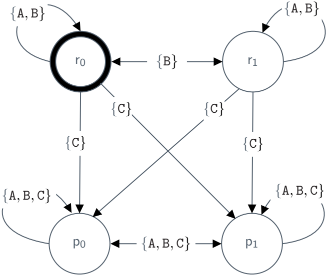
$$\begin{cases} w & = \{(\mathtt{ag}, \{w, w'\}), (\mathtt{C}, \{v, v'\}), \\ & \quad \texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}, \texttt{heads}\} \\ w' & = \{(\mathtt{ag}, \{w, w'\}), (\mathtt{C}, \{v, v'\}), \\ & \quad \texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}\} \end{cases}$$

where v, v', are defined as before.

where $\mathtt{ag} \in \{\mathtt{A}, \mathtt{B}\}$

Execution of $\text{open}\langle \mathtt{A} \rangle$

Side to side Execution



$M_3[\pi](r_0) = \{\texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}, \texttt{heads}\}$
$M_3[\pi](r_1) = \{\texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}\}$
$M_3[\pi](p_0) = M_1[\pi](p_0)$
$M_3[\pi](p_1) = M_1[\pi](p_1)$

$$\begin{cases} z & = \{(\texttt{A}, \{z\}), (\texttt{B}, \{z, z'\})(\texttt{C}, \{v, v'\}), \\ & \quad \texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}, \texttt{heads}\} \\ z' & = \{(\texttt{A}, \{z'\}), (\texttt{B}, \{z, z'\})(\texttt{C}, \{v, v'\}), \\ & \quad \texttt{look(ag)}, \texttt{key(A)}, \texttt{opened}, \} \end{cases}$$

where the possibilities v, v′ are defined as before.

where $\texttt{ag} \in \{\texttt{A}, \texttt{B}\}$

Execution of peek$\langle\texttt{A}\rangle$