Efficient Multi-agent Epistemic Planning: Teaching Planners About Nested Belief

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Contribution

We formally characterize a notion of multi-agent epistemic planning, and demonstrate how to solve a rich subclass of these problems using classical planning techniques.

General Approach

1. Model how the actions update both the state of the world and the agents' belief of that state
2. Assume a single nesting of belief is a fluent and convert to a classical planning problem
3. Reformulate the problem to maintain desired properties

Classical Planning

Planning Problem $\langle F, G, I, O\rangle$ where,

- F: set of fluent atoms
- G: set of fluents describing the goal condition
- I: setting of the fluents describing the initial state
- O: set of operators of the form $\langle Pre, \mathit{eff}^+, \mathit{eff}^-\rangle$
  - Pre: set of fluents for the precondition
  - eff^+: set of conditional effects that add a fluent
  - eff^-: set of conditional effects that delete a fluent
  - $(\langle \mathcal{C}^+, \mathcal{C}^-\rangle \to l)$: conditional effect that fires when $\mathcal{C}^+$ holds and $\mathcal{C}^-$ does not hold

E.g., PickupBlock

- If the agent is strong and the block is not slippery, then the agent holds the block: eff^+ contains $(\langle\{strong\}, \{slippery\}\rangle \to holding\_block)$
- If the block is big, then the agent's hand will no longer be free (i.e., we should delete the $hand\_free$ fluent): eff^- contains $(\langle\{big\_block\}, \emptyset\rangle \to hand\_free)$

Note: We distinguish between $\mathcal{C}^+/\mathcal{C}^-$ and $\mathit{eff}^+/\mathit{eff}^-$ so that our encoding is more legible

Multi-Agent Epistemic Planning

- State represents our belief about the world
- Our belief includes the nested belief of others
- Action precondition / effects can mention belief

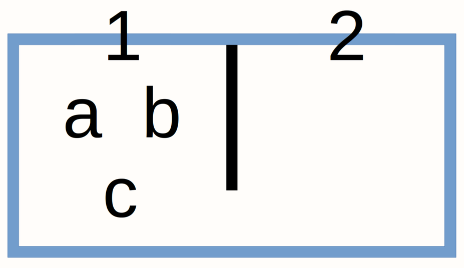
Encoded fluents are Restricted Modal Literals (RMLs):

$$\phi ::= p \mid B_{ag}\phi \mid \neg\phi$$

- $ag \in Ag$: A particular agent
- $p \in \mathcal{P}$: An original fluent without belief
- E.g., $B_{Sue} raining$: "Sue believes it is raining"

Key Issue: How do we maintain properties on the state of the world, such as believing logical deductions or never believing contradictory information? *Additional effects*

Example: Grapevine



Agents each have their own secret to (possibly) share with one another and start knowing only their own secret. They can move freely between a pair of rooms, and broadcast any secret they currently believe to everyone in the room.

Actions: $share(i, secret_j, room_k)$ (i and j may differ), $move\_left(i)$, and $move\_right(i)$

Goal: Misconception – one agent believes another does not know their secret, when in fact they do.

Solution: Consider a goal of $\{B_a secret_b, \neg B_b B_a secret_b\}$

$$[\,move\_right(a), share(b, secret_b, 1), move\_right(c), share(c, secret_b, 2)\,]$$

Example Effect

E.g., Consider the action $share(c, secret_b, room_1)$
Precondition: $\{at\_c\_room_1,\ B_c secret_b\}$
One effect: If a is in the room, they will learn the secret:

$$(\langle\{at\_a\_room_1\}, \emptyset\rangle \to B_a secret_b) \in \mathit{eff}^+$$

Ancillary Conditional Effects

Idea: Compile new conditional effects from existing ones in order to ensure certain properties hold

Negation Removal

Delete the negation of any added RML

$$(\langle \mathcal{C}^+, \mathcal{C}^-\rangle \to l) \in \mathit{eff}^+$$
$$\Rightarrow (\langle \mathcal{C}^+, \mathcal{C}^-\rangle \to \neg l) \in \mathit{eff}^-$$

E.g., $(\langle\{at\_a\_room_1\}, \emptyset\rangle \to B_a secret_b) \in \mathit{eff}^+$
$\Rightarrow (\langle\{at\_a\_room_1\}, \emptyset\rangle \to \neg B_a secret_b) \in \mathit{eff}^-$

Uncertain Firing

If we are uncertain if an effect fires, we should be uncertain about the original outcome of the effect

E.g., $(\langle\{at\_a\_room_1\}, \emptyset\rangle \to B_a secret_b) \in \mathit{eff}^+$
$\Rightarrow (\langle\emptyset, \{\neg at\_a\_room_1\}\rangle \to \neg B_a secret_b) \in \mathit{eff}^-$

KD45$_n$ Closure

The agent's belief should remain deductively closed under the logic of KD45$_n$ (e.g., $B_i p \vdash_{KD45} \neg B_i \neg p$)

E.g., $(\langle\{at\_a\_room_1\}, \emptyset\rangle \to B_a secret_b) \in \mathit{eff}^+$
$\Rightarrow (\langle\{at\_a\_room_1\}, \emptyset\rangle \to \neg B_a \neg secret_b) \in \mathit{eff}^+$

KD45$_n$ Unclosure

Remove anything that would deduce a delete effect.

E.g., $(\langle\emptyset, \emptyset\rangle \to \neg B_a secret) \in \mathit{eff}^-$
$\Rightarrow (\langle\emptyset, \emptyset\rangle \to B_a \neg secret) \in \mathit{eff}^-$

Conditioned Mutual Awareness

Idea: Given condition μ_i for agent i to witness an action, add the effects to update our belief about agent i

Examples for μ_i:

- in_room_i: Agent i observes effect if they are in the room (i.e., physically present).
- $True$: Agent i always observes the effect
- $False$: Agent i never observes the effect

E.g., $(\langle\emptyset, \{\neg at\_a\_room_1\}\rangle \to \neg B_a secret_b) \in \mathit{eff}^-$
$\Rightarrow (\langle\{\neg B_c \neg at\_a\_room_1\}, \emptyset\rangle \to \neg B_c \neg B_a secret_b) \in \mathit{eff}^+$

Preliminary Evaluation

- Ag: The set of agents included
- g: Size of the goal specification
- d: Maximum depth of nested belief
- $\vec{o}$: Computed plan
- **Solve**$_{(old)}$: Time to find a plan (old solver)
- **Comp**: Time to compile theory
- **Total**: Total time for both

Communication

Time (s)			
Solve$_{old}$	Solve	Comp.	Total
17.52	0.08	0.70	0.78
10.88	0.13	1.14	1.27
659.21	10.67	1.09	11.76
1607.87	18.29	1.77	20.06

Grapevine

$\|Ag\|$	$\|g\|$	d	$\|\vec{o}\|$		Time (s)		
			RPMEP	EFP2	RPMEP	EFP2	EFP2$_{simp}$
4	2	1	4	4	0.46	39.40	0.67
4	4	1	6	6	0.47	2698.30	100.22
4	8	1	12	TO	0.46	TO	-
4	2	2	5	4	9.28	48.43	0.91
4	4	2	7	6	9.26	3413.02	14.37
4	8	2	27	TO	9.76	TO	-

Summary

- Multi-agent planning settings often require us to model the nested belief of agents
- We leveraged a tractable fragment of epistemic reasoning to maintain consistency of agents' belief
- Realized an automated planning system that deals with the nested belief in a multi-agent setting

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