Epistemic Planning: Semantic Approach

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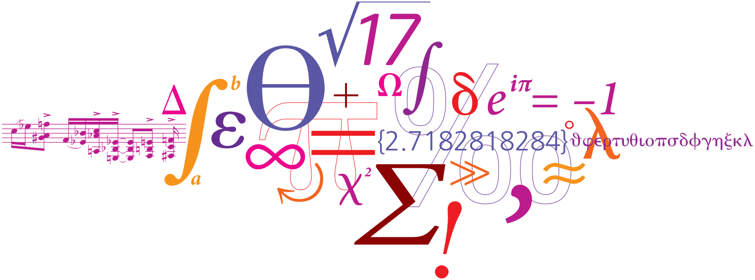

DTU Compute
Department of Applied Mathematics and Computer Science

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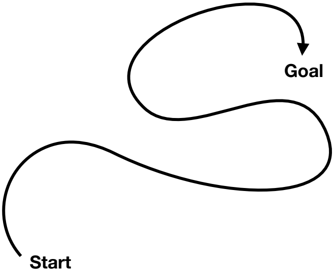
Epistemic planning =
automated *planning* + Theory of Mind reasoning

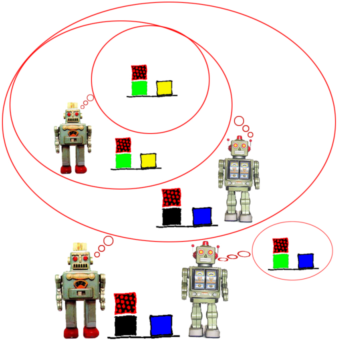
Aim: To compute plans that can take the mental states of other agents into account.

Essentially: (Decentralised) **multi-agent planning** in environments with (potentially higher-order) **information asymmetry**.



Automated planning

+



Logical reasoning about the mental states of other agents

Syntactic vs semantic, explicit vs implicit

When moving from standard propositional states to states including a Theory of Mind, there are two distinct paths one might take.

- **Syntactic approach**: States are (sets of) formulas (e.g. formulas of S5 epistemic logic)
- **Semantic approach**: States are semantic models (e.g. epistemic models = Kripke models).

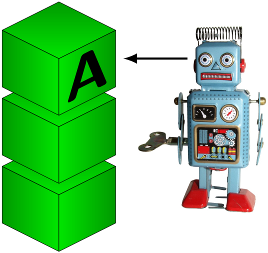
Note: For propositional planning under full observability, the approaches are trivially equivalent.

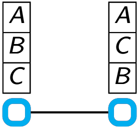
Furthermore, for the semantic approach, there is a choice between:

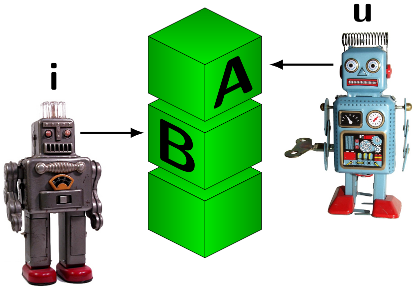
- **Explicit approach**: Full state space is assumed given, and solution concept is defined directly in terms of this. E.g. logics like ATEL and CSL. [van der Hoek and Wooldridge, 2002, Jamroga and Aagotnes, 2007]
- **Implicit approach**: State space is induced by initial state and action library (as in classical STRIPS/PDDL planning).

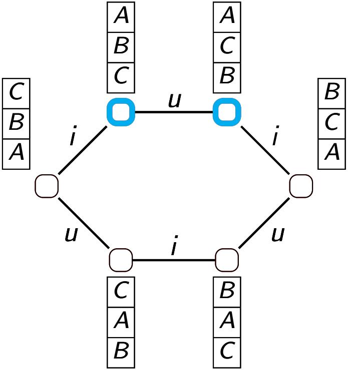
DEL-based epistemic planning is *implicit* and *semantic*.

[Bolander and Andersen, 2011]









Epistemic states: Multi-pointed epistemic models of multi-agent S5. Nodes are **worlds**. **Designated worlds**: ▢ (those considered possible by planning agent).

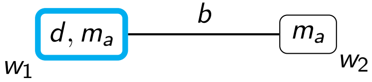
The coordinated attack problem in dynamic epistemic logic (DEL)

Two generals (agents), a and b. They want to coordinate an attack, and only win if they attack simultaneously.

d: "general a will attack at dawn".

m_i: the messenger is at general i (for $i = a, b$).

Initial **epistemic state**:

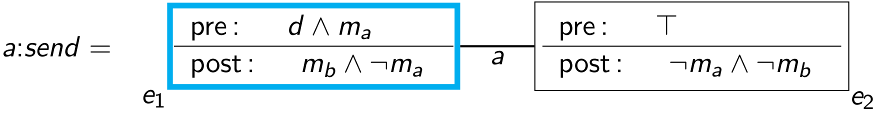
$s_0 =$ 

Nodes are **worlds**, edges are **indistinguishability edges** (reflexive loops not shown).

The coordinated attack problem in dynamic epistemic logic (DEL)

Recall: d means "a attacks at dawn"; m_i means messenger is at general i.

Available **epistemic actions** (aka **action models** aka **event models**):



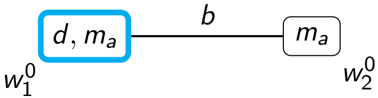
And symmetrically an epistemic action $b{:}send$. We read $i{:}\alpha$ as "agent i does α".

Nodes are **events**, and each event has a **precondition** and a **postcondition** (effect). The precondition is an epistemic formula and the postcondition is a conjunction of literals.

[Baltag et al., 1998, van Ditmarsch and Kooi, 2008]

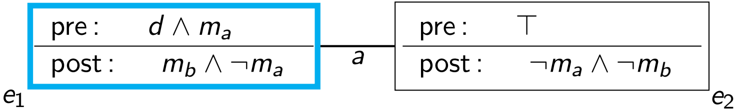
The product update in dynamic epistemic logic

$s_0 =$

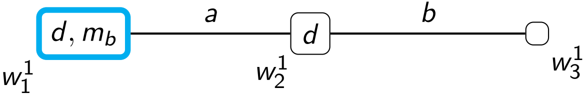


$s_0 \models K_a d \wedge \neg K_b d$

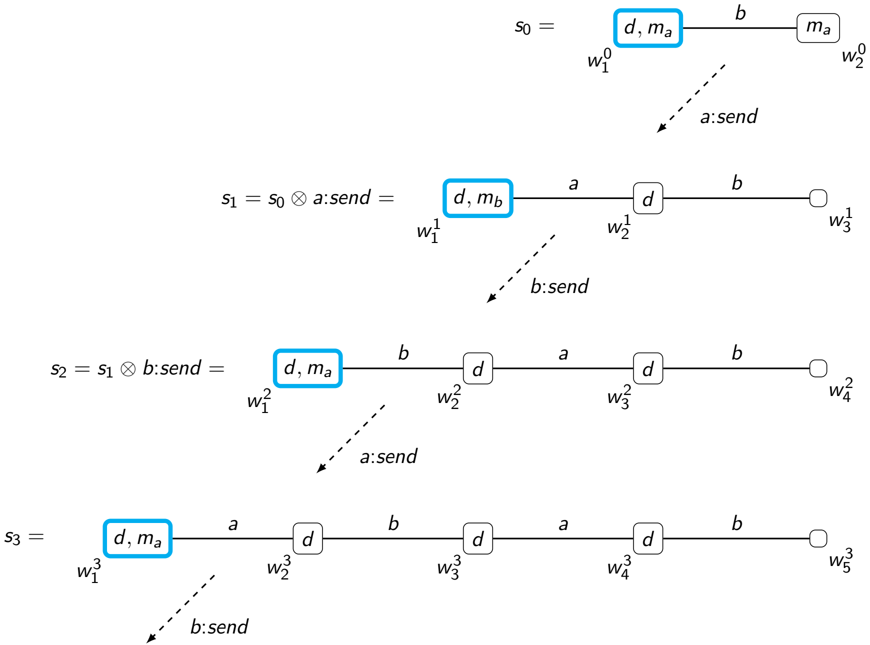
$a{:}send =$



$s_0 \otimes a{:}send =$



$s_0 \otimes a{:}send \models K_a d \wedge K_b d \wedge \neg K_a K_b d$



$s_0 =$
d, m_a
b
m_a
w_1^0
w_2^0
a:send
$s_1 = s_0 \otimes a$:send $=$
d, m_b
a
d
b
w_1^1
w_2^1
w_3^1
b:send
$s_2 = s_1 \otimes b$:send $=$
d, m_a
b
d
a
d
b
w_1^2
w_2^2
w_3^2
w_4^2
a:send
$s_3 =$
d, m_a
a
d
b
d
a
d
b
w_1^3
w_2^3
w_3^3
w_4^3
w_5^3
b:send

Epistemic planning tasks

Definition. An **epistemic planning task** (or simply a **planning task**) $T = (s_0, A, \gamma)$ consists of an epistemic state s_0 called the **initial state**; a finite set of epistemic actions A; and a **goal formula** γ of the epistemic language.

Definition. A (sequential) **solution** to a planning task $T = (s_0, A, \gamma)$ is a sequence of actions $\alpha_1, \alpha_2, \dots, \alpha_n$ from A such that for all $1 \leq i \leq n$, α_i is applicable in $s_0 \otimes \alpha_1 \otimes \cdots \otimes \alpha_{i-1}$ and

$$s_0 \otimes \alpha_1 \otimes \alpha_2 \otimes \cdots \otimes \alpha_n \models \gamma.$$

Example. Let s_0 be the initial state of the coordinated attack problem. Let $A = \{a{:}send, b{:}send\}$. Then the following are planning tasks:

1. $T = (s_0, A, Cd)$, where C denotes common knowledge. It has no solution.
2. $T = (s_0, A, E^n d)$, where E denotes "everybody knows" and $n \geq 1$. It has a solution of length n.

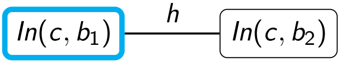
[Bolander et al., 2020]

Epistemic planning example: Get the cube

- **Objects**: $\mathcal{O} = \{b_1, b_2, c\}$, two boxes b_1 and b_2, and a cube c.
- **Agents**: $\mathcal{A} = \{h, a\}$, a human h and a robot r. The robot is the planning agent.
- **Atomic propositions**: $In(x, y)$ means x is in y, where $x, y \in \mathcal{O} \cup \mathcal{A}$ (when $y \in \mathcal{A}$, it means y is holding x).

Initial epistemic state:

$s_0 =$



The goal is for the human to hold the red cube, $In(r, h)$.

Actions specialised for the case of $\mathcal{O} = \{b_1, b_2, c\}$.

Agent i (semi-privately) **peeks** into box x:

$i{:}peek(x) =$ [pre: $In(c, x)$] —$\mathcal{A} - \{i\}$— [pre: $\neg In(c, x)$]

Agent i (publicly) **picks up** object x from y:

$i{:}pickup(x, y) =$

pre:	$In(x, y)$
post:	$In(x, i) \wedge \neg In(x, y)$

Agent i (publicly) **puts** object x in y:

$i{:}putdown(x, y) =$

pre:	$In(x, i)$
post:	$In(x, y) \wedge \neg In(x, i)$

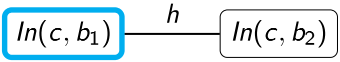
Agent i (publicly) **announces** that formula φ is true:

$i{:}ann(\varphi) =$ [pre: φ]

Get the cube: Planning task and solutions

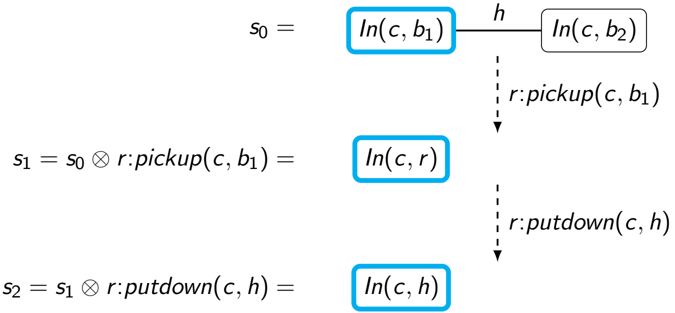
The planning task T has the actions of the previous slide and initial state s_0 and goal γ given by:

$s_0 =$



$\gamma = In(r, h)$

Solution to T, by robot R:



Applicability, perspective shifts, implicit coordination

Seemingly simpler solution: $h{:}pickup(c, b_1)$. But intuitively, this shouldn't work, since the human doesn't know the cube is in box 1...

Applicability: An action α is **applicable** in a state s if for each designated world w of s there is a designated event e of α with $w \models pre(e)$.

Perspective shift: The **perspective shift** of state s to agent i, denoted s^i, is achieved by closing under the indistinguishability relation of i. We call s^i the **perspective** of agent i on state s.

Example. $h{:}pickup(c, b_1)$ is not applicable in s_0 from h's perspective.

Implicitly coordinated solution to planning task: Each action has to be applicable from the perspective of the acting agent; and the product update $s \otimes i{:}\alpha$ is replaced by $s^i \otimes i{:}\alpha$.

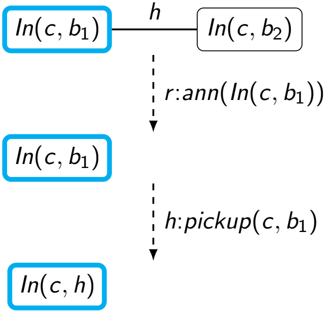
Get the cube: Implicit coordination

Joint solution to T, by robot R, implicitly coordinated:

$$s_0 =$$

$$s_1 = s_0 \otimes r{:}ann(In(c, b_1)) =$$

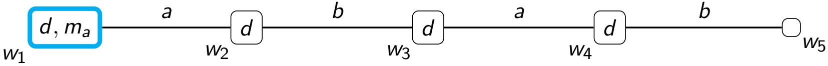
$$s_2 = s_1 \otimes h{:}pickup(c, b_1) =$$



If purely epistemic actions (announcements) have a lower cost than ontic actions (moving things around), the solution above is the only optimal one.

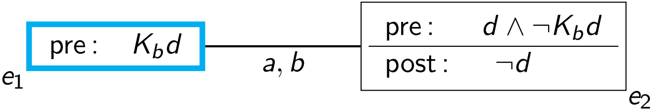
Undecidability: lengthening and shortening chains

Consider a chain produced by the coordinated attack problem:



Using preconditions of modal depth 1 we can shorten the chain by 1:

shorten =



We can now both lengthen (by *send*) and shorten chains (by *shorten*), and this allows us to encode two-counter machines ⇒ undecidability of the plan existence problem!

Undecidability holds even with preconditions of modal depth 1, and for purely epistemic planning (no postconditions) even for modal depth 2. [Bolander and Andersen, 2011, Charrier et al., 2016, Bolander et al., 2020]

Some of the current challenges in epistemic planning

- **Undecidability issues**: open complexity problems.
  [Bolander et al., 2020]
- **State size explosion problems**: find compact state representations.
  [Charrier and Schwarzentruber, 2017, van Benthem et al., 2018]
- **The belief-revision problem in DEL**: How to recover from false beliefs without an underlying epistemic relation. Relates to the state size explosion problem.
- **Heuristics for epistemic planning**: to reduce all of the above mentioned complexity and scalability issues
- **Languages**: syntactic languages for describing actions.
  [Baral et al., 2012, Baral et al., 2013]

This, and much more, is discussed in the "Epistemic Planning" special issue of AIJ currently being finalised.

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