From Dynamic Epistemic Logic to Socially Intelligent Robots

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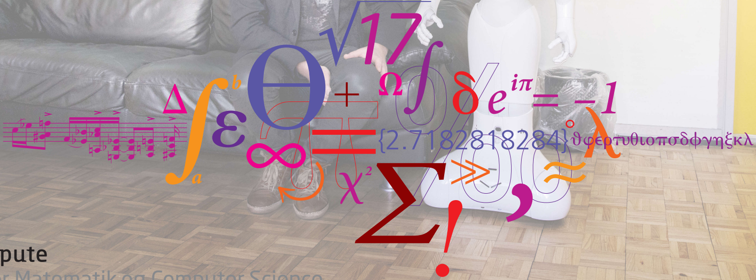
WoLLIC 2023



DTU Compute
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Automated planning: Classical planning tasks

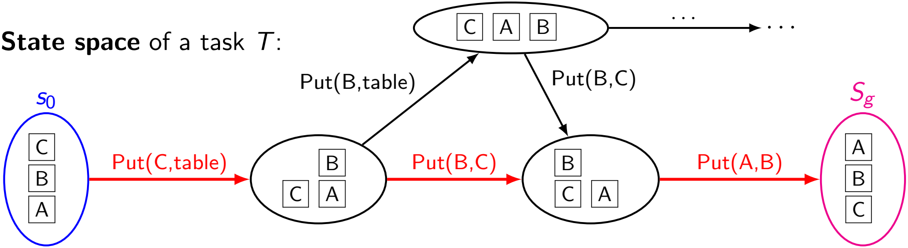
Definition (Adopted from [Ghallab et al., 2004])

A **classical planning task** (over states S) is $T = (s_0, A, \circ, S_g)$, where

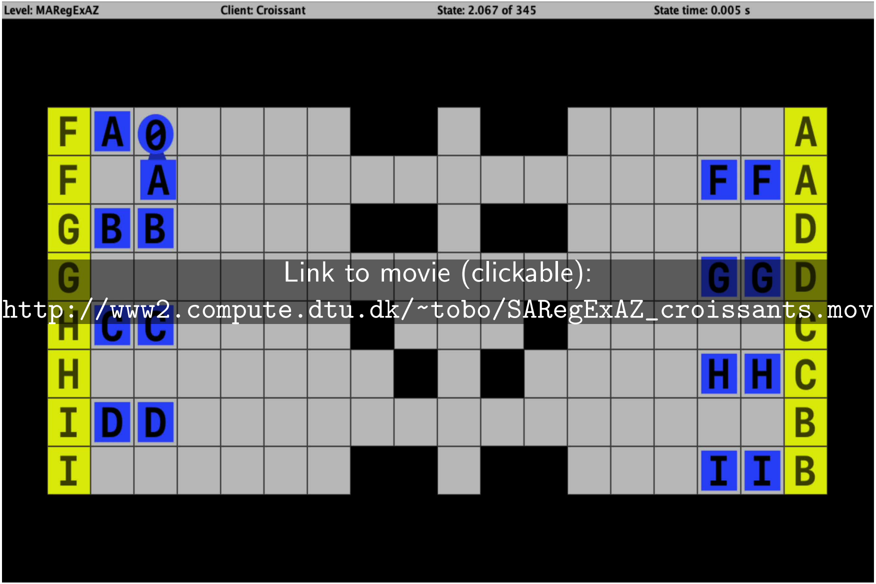
- $s_0 \in S$ is an **initial state**.
- A is a finite set of available **actions**.
- $\circ$ is a state-transition operator: for $s \in S, \alpha \in A$, either $s \circ \alpha \in S$ or $s \circ \alpha$ is undefined (and in that case we say α is **inapplicable** in s).
- $S_g \subseteq S$ is a set of **goal states**.

A **solution** to a classical planning task $(s_0, A, \circ, S_g)$ is a sequence of actions (a **plan**) $\pi = \alpha_1, \ldots, \alpha_n$ from A such that $s \circ \alpha_1 \circ \cdots \circ \alpha_n \in S_g$.

State space of a task T:

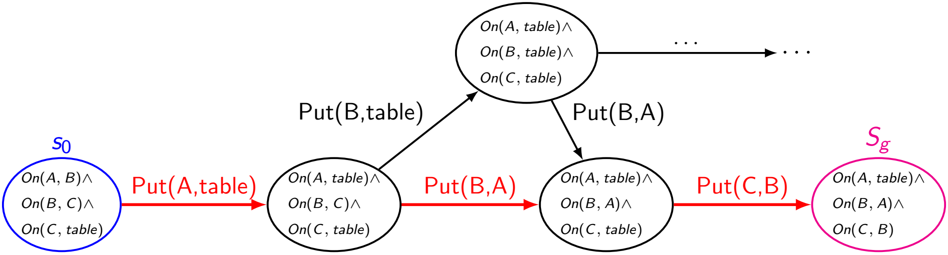


Classical planning task example (and a solution to it)



Link to movie (clickable):
http://www2.compute.dtu.dk/~tobo/SARegExAZ_croissants.mov

Action schemas



Action schema describing the $Put(x, y)$ action for put object x on top of object y:

ACTION : $Put(x, y)$
PRECONDITION : $On(x, z) \wedge \cdots$
EFFECT : $On(x, y) \wedge \neg On(x, z)$

pre :	$On(x, z) \wedge \cdots$
post :	$On(x, y) := \top$ $On(x, z) := \bot$

[Ghallab et al., 2004, Baltag et al., 1998, van Ditmarsch and Kooi, 2008]

Adding non-determinism and partial observability

start state

$On(A, B) \wedge$
$On(B, C) \wedge$
$On(C, Table)$

$On(A, C) \wedge$
$On(C, B) \wedge$
$On(B, Table)$

belief state

$\circ$

action: $Put(A, table)$

pre :	$On(A, y) \wedge \cdots$
post :	$On(A, table) := \top$ $On(A, y) := \bot$

success

pre :	$On(A, y) \wedge \cdots$
post :	

failure

$=$

resulting state

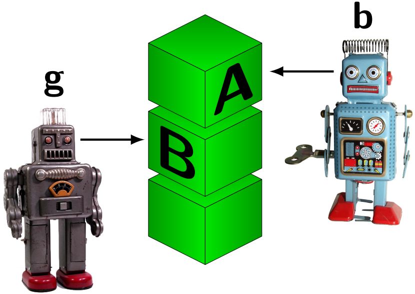
$On(A, table) \wedge$
$On(B, C) \wedge$
$On(C, Table)$

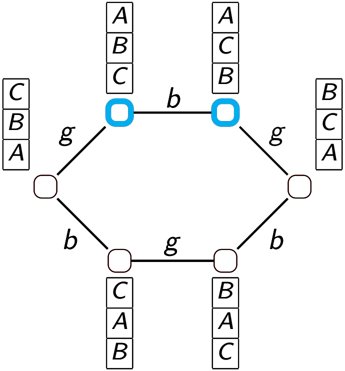
$On(A, table) \wedge$
$On(C, B) \wedge$
$On(B, Table)$

$On(A, B) \wedge$
$On(B, C) \wedge$
$On(C, Table)$

$On(A, C) \wedge$
$On(C, B) \wedge$
$On(B, Table)$

Multiagent case: States as S5 Kripke models





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

Agent b: "Which letter does the middle block have?"
(Public Announcement Logic, PAL [Plaza, 1989])

Implicit coordination

Suppose the agents have a **joint goal** (like stacking blocks in reverse alphabetic order), and **plan independently**. We use notation $i{:}\alpha$ for "agent i does α".

An fully observant agent c might form this plan (where the blocks are numbered 1–3 according to their initial stacking order):

$$b{:}Put(1, table), g{:}Put(2, 1), b{:}Put(3, 2).$$

However, it's not a **verifiable** solution by b and g.

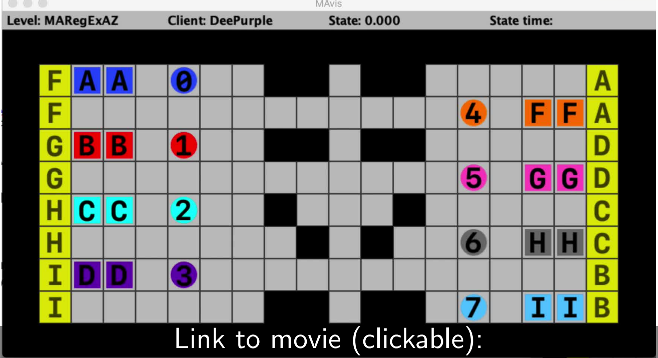
Perspective shift: The **perspective shift** of state s to agent i, denoted s^i, is achieved by closing under the indistinguishability relation of i. We call s^i the **perspective** of agent i on state s.

Redefined solution concept: A **plan** is $i_1{:}\alpha_1, \ldots, i_n{:}\alpha_n$ such that

$$(\cdots((s_0^{i_1} \circ i_1{:}\alpha_1)^{i_2} \circ i_2{:}\alpha_2)^{i_3} \circ \cdots \circ i_{n-1}{:}\alpha_{n-1})^{i_n} \circ i_n{:}\alpha_n \in S_g$$

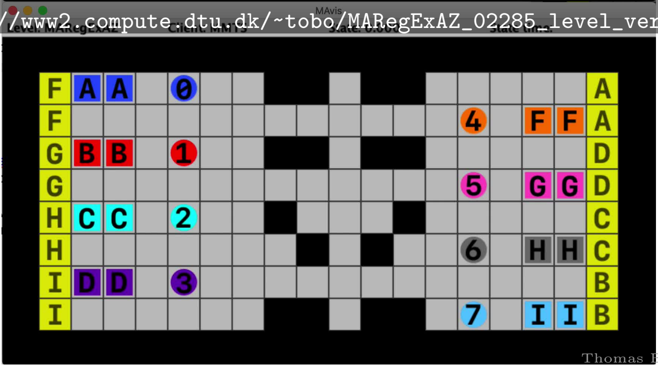
Problem: Only assumes other agents to be rational in the future.
Solution: Introduce forward induction (work in progress).

[Engesser et al., 2017, Bolander et al., 2016]

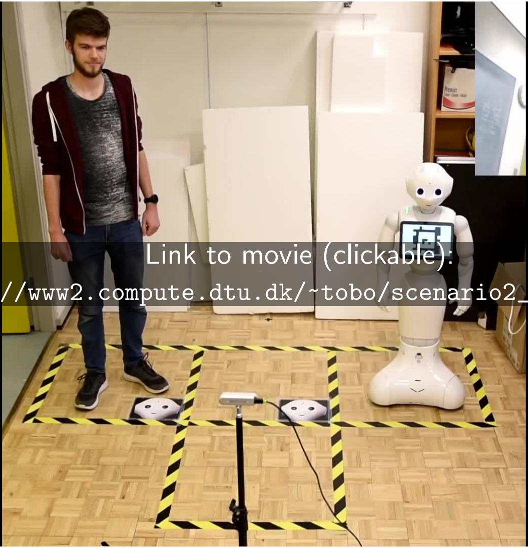


Link to movie (clickable):

http://www2.compute.dtu.dk/~tobo/MARegExAZ_02285_level_vert.mov



Multi-agent pathfinding with destination uncertainty

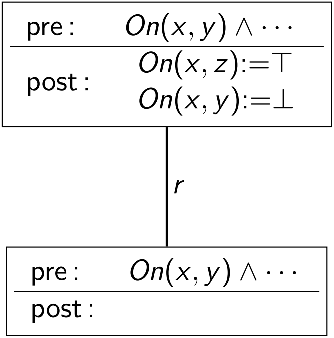


Link to movie (clickable):

http://www2.compute.dtu.dk/~tobo/scenario2_double.mov

[Nebel et al., 2019, Bolander et al., 2021]

Introducing partially observable actions



This is an **event model** of dynamic epistemic logic (DEL)...

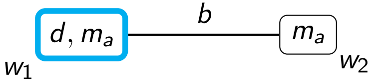
Dynamic epistemic logic (DEL) via example: The coordinated attack problem

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**:

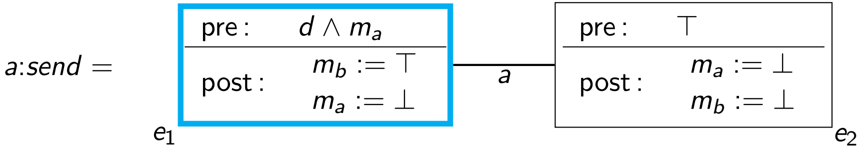
$s_0 =$ 

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

Event models of 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**):

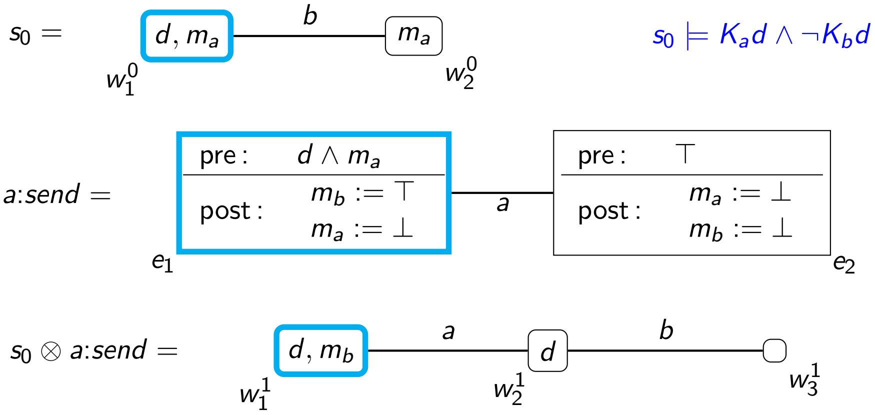


And symmetrically an epistemic action b:$send$. We read $i{:}\alpha$ as "agent i does α".

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.

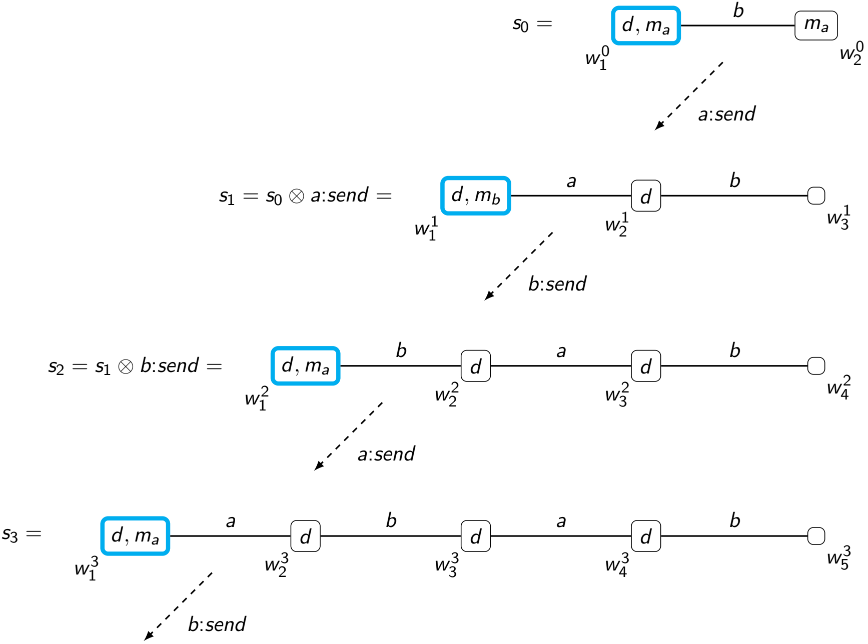
[Baltag et al., 1998, van Ditmarsch and Kooi, 2008, Bolander et al., 2021]

The product update in dynamic epistemic logic



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

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


$s_0 =$
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**) $T = (s_0, A, \varphi_g)$ consists of an epistemic state s_0 called the **initial state**; a finite set of epistemic actions A; and a **goal formula** φ_g of the epistemic language.

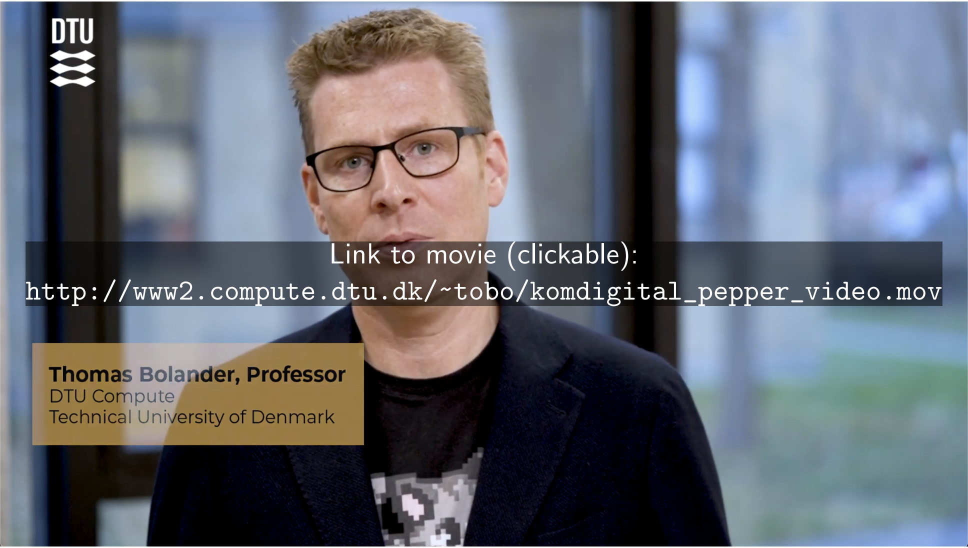
Definition. A (sequential) **solution** to a planning task $T = (s_0, A, \varphi_g)$ is a sequence of actions $\alpha_1, \alpha_2, \ldots, \alpha_n$ from A such that for all $1 \leq i \leq n$, α_i is applicable in $s_0 \otimes \alpha_1 \otimes \cdots \otimes \alpha_{i-1}$ and

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

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:

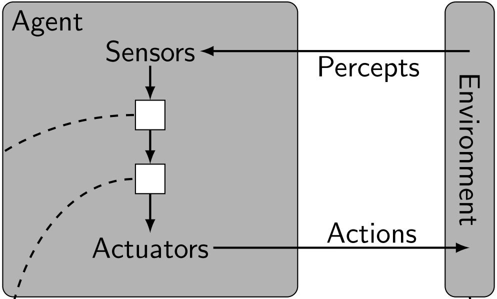
1. $T = (s_0, A, Cd)$, where C denotes common knowledge. It has no solution.
2. $T = (s_0, A, E^n d)$, where E denotes "everybody knows" and $n \geq 1$. It has a solution of length n.

[Bolander et al., 2020]



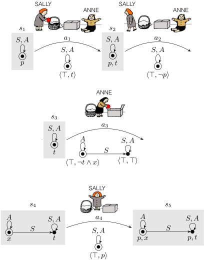
Link to movie (clickable):
http://www2.compute.dtu.dk/~tobo/komdigital_pepper_video.mov

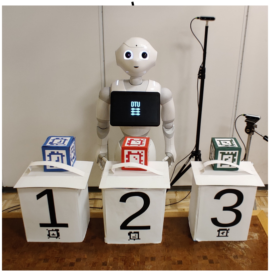
KomDigital: R2DTU – A Pepper robot, 25 November 2020 [?]



perception layer:
deep neural networks (subsymbolic)

cognition layer:
DEL + planning (symbolic)

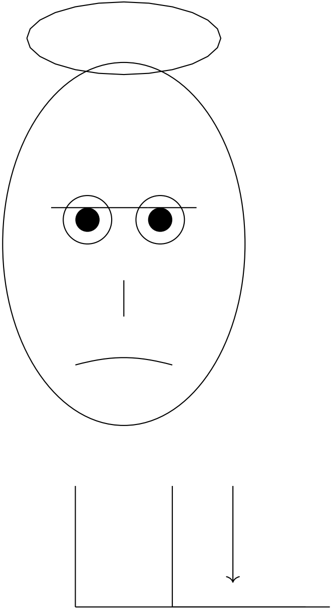




Why not just make ChatGPT or GPT-4 do it all?

GPT-4 can do amazing things.

Example. My Input to GPT-4: "Provide tikz code for an illustration of Kurt Gödel, the famous logician who proved the incompleteness theorems."



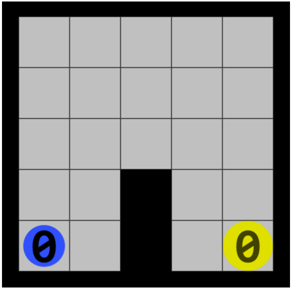
Kurt Gödel

TO

Suppose you're controlling a robot in a grid world. The robot can in each move move one cell north, east, west or south. The grid cells are labelled by coordinates with (1,1) in the lower left corner. Assume you want to move the robot from (1,1) to (5,1) and assume there are walls in cell (3,1) and (3,2). The robot can't move through wall cells. Please devise a plan for the robot, i.e., a sequence of moves that brings it from the initial state, (1,1), to the goal state, (5,1).

One possible solution could be:

1. Move the robot east to (2,1).
2. Move the robot east to (3,1).
3. Move the robot north to (3,2).
4. Move the robot west to (2,2).
5. Move the robot south to (2,1).
6. Move the robot east to (3,1).
7. Repeat steps 4 to 6 until the robot reaches (5,1).



Plan existence problem

Definition. $\mathcal{T}(m,n)$ is the class of epistemic planning tasks where all actions have preconditions of modal depth $\leq m$ and postconditions of modal depth $\leq n$. We use $n = -1$ to denote the case without postconditions.

in $\mathcal{T}(0,0)$

pre :	$p \wedge q$
post :	$p{:=}\bot$ $r{:=}\top$

in $\mathcal{T}(2,-1)$

pre :	$K_b K_g On(C,B)$
post :	

in $\mathcal{T}(1,1)$

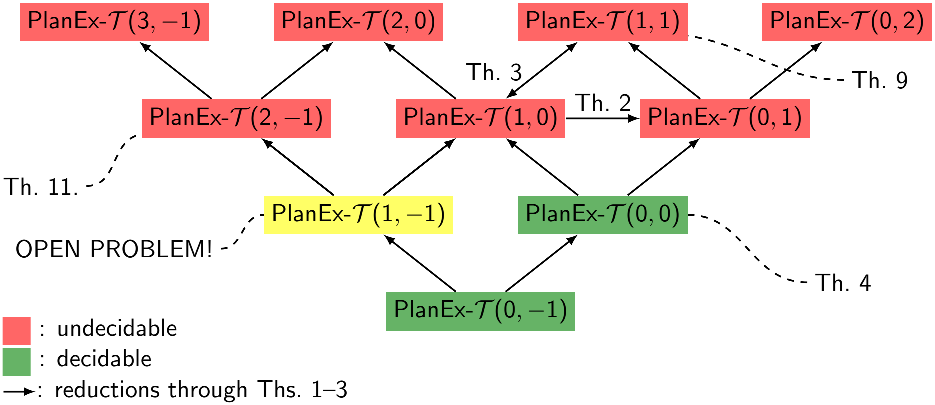
pre :	$K_1 p$
post :	$p{:=}K_2 q$

Definition. PlanEx-$\mathcal{T}(m,n)$ is the following decision problem: Given a planning task $T \in \mathcal{T}(m,n)$, does T have a solution?

[Bolander et al., 2020]

The border between decidability and undecidability

Theorem 1. *PlanEx*-$\mathcal{T}(m,n) \leq^P$ *PlanEx*-$\mathcal{T}(m+k, n+l)$.
Theorem 2. *PlanEx*-$\mathcal{T}(m,n) \leq^P$ *PlanEx*-$\mathcal{T}(0,1)$.
Theorem 3. *PlanEx*-$\mathcal{T}(m,n) \leq^P$ *PlanEx*-$\mathcal{T}(1,0)$.



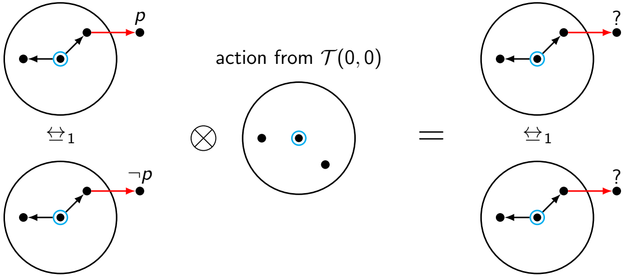
[Bolander and Andersen, 2011, Aucher and Bolander, 2013, Yu et al., 2013, Charrier et al., 2016, Cong et al., 2018, Bolander et al., 2020]

Decidability theorem

k-**bisimilarity**: Satisfying back and forth conditions of bisimilarity up to depth k. Guarantees modal equivalence up to modal depth k.

Theorem 4. *PlanEx-*$\mathcal{T}(0,0)$ *is decidable.*

Proof idea: k-bisimilarity is preserved when doing product update with epistemic actions having propositional pre- and post-conditions [Yu et al., 2013]; intuitively because the events of such actions cannot look deeper into the model.



$\mathcal{T}(0,0)$ examples

public announcements of propositional facts:

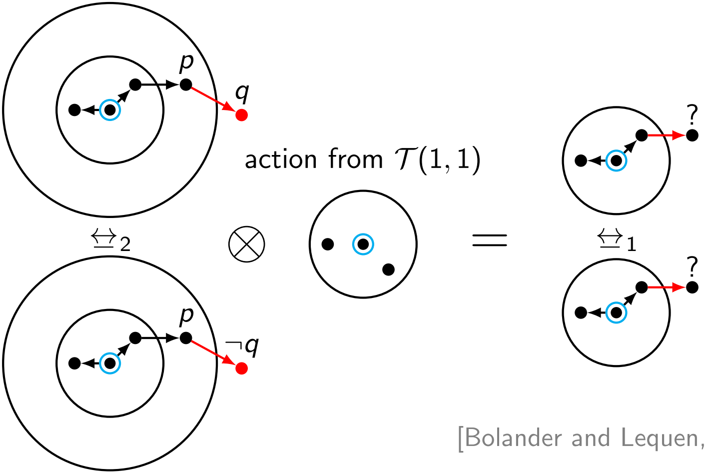
pre :	$p \wedge q$
post :	

STRIPS actions:

pre :	$p \wedge q$
post :	$p := \bot$ $r := \top$

Generalising the k-bisimilarity preservation result

Proposition 1. *Suppose s and s' are k-bisimilar and α is an action of $\mathcal{T}(m,n)$. Then $s \otimes \alpha$ and $s' \otimes \alpha$ are $(k - \max\{m,n\})$-bisimilar.*



[Bolander and Lequen, 2022]

Depth-bounded epistemic planning (w. in progress)

Planning algorithm $\textsc{Search}(T, k)$ with depth-bound k: breadth-first search (BFS) through the state space, exploiting Proposition 1:

- Whenever we apply action α to state s, we afterward do the k-bisimulation contraction, where k is the maximal bound guaranteeing preservation of k-bisimilarity.
- We terminate any path satisfying $k \leq \textit{modal-depth}(\varphi_g)$.

Parameters of planning task T (we study parameterised complexity).

a: number of agents.

c: maximal modal depth of preconditions of actions.

o: modal depth of goal formula.

p: number of propositional variables.

u: maximal length of plan.

Soundness. If $\textsc{Search}(T, k)$ returns π, then π is a solution to T.

Completeness. If T has a solution, it will be found by $\textsc{Search}(T, k)$ whenever $k \geq \mathsf{cu} + \mathsf{o}$.

Complexity. $\textsc{Search}(T, k)$ runs in time $\exp_2^{\mathsf{cu}+\mathsf{o}+1} \max\{\mathsf{a}, \mathsf{p}\}$.

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