Bachelor Thesis

How does a token based order compare to the asynchron order in multi-agent plan executions?

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Declaration

I hereby declare, that I am the sole author and composer of my thesis and that no other sources or learning aids, other than those listed, have been used. Furthermore, I declare that I have acknowledged the work of others by providing detailed references of said work.
I hereby also declare, that my Thesis has not been prepared for another examination or assignment, either wholly or excerpts thereof.

Place, Date	Signature

Abstract

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Zusammenfassung

German version is only needed for an undergraduate thesis.

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1 Introduction

How would it be if we had a perfect execution order?

This thesis is trying to answer that question by looking at the different execution orders. In other pieces of writing about epistemic planning the execution order is a seemingly random one, usually unclear. This is easier to describe mathematically, but it also has some drawbacks. My thesis is trying to take these games and transform them into a game with a token. As you will see, this will have some advantages.

There are four different execution modes that are possible:

1. Asynchronous

   The agents move in a seemingly random order.

2. Concurrent

   The agents can act at the same time.

3. token based

   The agents need a special token to be able to act, only one agent has the token at a time.

4. round robin

   The agents act one agent after the other, after the last agent is done they begin with the first agent again.

We have found that the token based orders are a subset of the asynchronous orders, because all token based orders can also be “a random” asynchronous order, but not all asynchronous orders are a token based order. Also all round robin orders can be token based orders by accident, but not all token based orders are a round robin order.

Because of this we only looked at token based orders in this thesis.

Epistemic planning is taking regular planning and enriching it with knowledge and belief. In regular planning, the world is simplified so that everyone knows everything there is to know about that particular microverse. But this is not the real world. In the real world, agents often have only little knowledge and can therefore make only limited calculations on that world. To model that, we use epistemic logic. To show that the agents each have different knowledge that can change over time, we describe the logic as being dynamic.

How old is epistemic planning?

What is the future of epistemic planning?

Why is this research relevant?

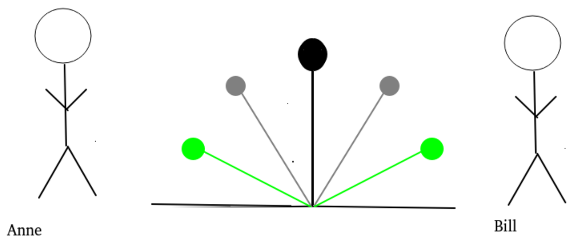
2 Related Work

Give a brief overview of the work relevant for your thesis.

This thesis is building up from the paper “Better eager than lazy” [1] from my advisors. In this paper, they researched how a lazy agent, who had a preference against doing its own actions, compares to eager agents in planning problems.

3 Background

Imagine there is a lever between two players, Anne and Bill. It is upright in the middle position and has 5 positions in total. Anne thinks the lever should be pulled two positions to her side and Bill thinks the lever should be pulled two positions to his side.



With the asynchronous execution order this game could be easily finished if Anne or Bill just pulled the lever two times in their direction. But just as easily this game could go on a really long time, if Anne and Bill pulled the lever alternating, once to the right and then to the left, then to the right again and so on. This could go on infinitely. With no set execution order, how can we prevent the game from going on infinitely?

The definitions are taken from the “Better eager than lazy” (2018) [1] paper, the “A gentle introduction to DEL” (2017) [2] and the book “Dynamic epistemic logic” from Ditmarsch [3].

3.1 DEL

DEL, or Dynamic Epistemic Logic is a specific mathematical language used as the framework. Let $\mathcal{A}$ be a finite set of agents, in this case $\mathcal{A} = \{\text{Anne, Bill}\}$. Let $\mathcal{P}$ be a finite set of atomic propositions. Atomic propositions, like p or q, describe some affairs that can be true or false. The epistemic language $\mathcal{L}_{\text{KC}}$ is:

$$\varphi ::= \top \mid \bot \mid p \mid \neg\varphi \mid \varphi \wedge \varphi \mid K_i\varphi \mid C\varphi$$

with $p \in \mathcal{P}$ and $i \in \mathcal{A}$. $\top$ describes φ as always being true, $\bot$ as always false. $K_i\varphi$ reads as "Agent i knows φ". $C\varphi$ reads as "it is common knowledge that φ ". Let's look back at the example. The two agents, a (Anne) and b (Bill) have two goal positions, goal p (lever to the left) and q (lever to the right). Anne knows that one goal position is the left, but does not know the other: $K_a p \wedge \neg K_a q$. Bill knows that one goal position is the right, but does not know the other position: $\neg K_b p \wedge K_b q$.

Formulas are evaluated in epistemic models

$$\mathcal{M} = (W, (\sim_i)_{i \in \mathcal{A}}, V)$$

with the domain W being a nonempty finite set of worlds, $\sim_i$ being an equivalence relation called the indistinguishably relation for agent $i \in \mathcal{A}$ and $V : P \to \mathcal{P}(W)$ assigning a valuation to each atomic proposition.

In the example above, Anne sees two worlds. One world where just the lever to the left is a goal, but also a world where another goal is the lever to the right. Those two worlds are indistinguishable for Anne.

(EXTEND: this should be written differently) For $W_d \subseteq W$, the pair $(\mathcal{M}, W_d)$ is called an epistemic state (or simply a state) and the worlds of W_d are called designated worlds. A state is called global if $W_d = \{w\}$ for some world w (called the actual world). We then often write $(\mathcal{M}, w)$ instead of $(\mathcal{M}, \{w\})$. We use $S^{gl}(P, \mathcal{A})$ to denote the set of global states (or simply S^{gl} if P and $\mathcal{A}$ are clear from context). For any state $s = (\mathcal{M}, W_d)$ we let $Globals(s) = \{(\mathcal{M}, w) | w \in W_d\}$. A state $(\mathcal{M}, W_d)$ is called a local state for agent i if W_d is closed under $\sim_i$ (that is, if $w \in W_d$ and $w \sim_i v$, then $v \in W_d$). Given a state $s = (\mathcal{M}, W_d)$ the associated local state of agent i, denoted s^i, is $(\mathcal{M}, \{v | v \sim_i w \text{ and } w \in W_d\})$. Going from s to s^i amounts to a *perspective shift* to the local perspective of agent i.

Let $(\mathcal{M}, W_d)$ be a state on $P, \mathcal{A}$ with $\mathcal{M} = (W, (\sim_i)_{i \in \mathcal{A}}, V)$. For $i \in \mathcal{A}$, $p \in P$ and $\varphi, \psi \in \mathcal{L}_{\text{KC}}(P, \mathcal{A})$, we define truth as follows:

$$
\begin{array}{lll}
(\mathcal{M}, W_d) \models \varphi & \text{iff} & (\mathcal{M}, w) \models \varphi \text{ for all } w \in W_d \\
(\mathcal{M}, w) \models p & \text{iff} & w \in V(p) \\
(\mathcal{M}, w) \models \neg\varphi & \text{iff} & (\mathcal{M}, w) \not\models \varphi \\
(\mathcal{M}, w) \models \varphi \wedge \psi & \text{iff} & (\mathcal{M}, w) \models \varphi \text{ and } (\mathcal{M}, w) \models \psi \\
(\mathcal{M}, w) \models K_i\varphi & \text{iff} & (\mathcal{M}, v) \models \varphi \text{ for all } v \sim_i w \\
(\mathcal{M}, w) \models C\varphi & \text{iff} & (\mathcal{M}, v) \models \varphi \text{ for all } v \sim^* w
\end{array}
$$

where $\sim^*$ is the transitive closure of $\bigcup_{i \in \mathcal{A}} \sim_i$.

(TODO: this still needs updating with top and bot)

Using Anne and Bill as an Example, Anne cannot distinguish between p, q and $p, \neg q$. Bill cannot distinguish between p, q and $\neg p, q$. A graphic representation of this would be the global state $s = (\mathcal{M}, w_2)$ with the nodes representing the worlds and the edges representing the indistinguishably relation. The circle around a node represent designated worlds.

$$s = \begin{tikzcd} \underset{w_1 : p, \neg q}{\bullet} \arrow[r, dash, "\text{Anne}"] & \underset{w_2 : p, q}{\odot} \arrow[r, dash, "\text{Bill}"] & \underset{w_3 : \neg p, q}{\bullet} \end{tikzcd}$$

3.1.1 Epistemic Actions and Product Updates

An event model is $\mathcal{E} = \langle E, (\sim_i)_{i\in\mathcal{A}}, pre, \mathit{eff}\rangle$ where the domain E is a non-empty finite set of events; $\sim_i \subseteq E \times E$ is an equivalence relation called the indistinguishably relation for agent i; $pre : E \rightarrow \mathcal{L}_{KC}$ assigns a precondition to each event; and $\mathit{eff} : E \rightarrow \mathcal{L}_{KC}$ assigns a post condition, or effect to each event. For all $e \in E$, $\mathit{eff}(e)$ is a conjunction of literals, that means atomic propositions and their negations, including $\top$ and $\bot$.
For $E_d \subseteq E$, the pair $(\mathcal{E}, E_d)$ is called an epistemic action, or simply action and the events in E_d are called a local action for agent i when E_d is closed under $\sim_i$.
Each event of an action represents a different possible outcome. By using multiple events $e, e' \in E$ that are indistinguishable ($e \sim e'$), it is possible to model only partially observable actions.
If the event model has $E = \{e\}$, we will write $\mathcal{E} = \rangle pre(e), \mathit{eff}(e)\langle$.

The product update is used to specify the next state resulting from performing an action in a state. Let a state $s = (\mathcal{M}, W_d)$ and an action $a = (\mathcal{E}, E_d)$ be given with $\mathcal{M} = \langle W, (\sim_i)_{i\in\mathcal{A}}, V\rangle$ and $\mathcal{E} = \langle E, (\sim_i)_{i\in\mathcal{A}}, pre, \mathit{eff}\rangle$ then the product update of s with a is defined as $s \otimes a = ((W', (\sim'_i)_{i\in\mathcal{A}}, W'_d))$ where :

- $W' = \{(w, e) \in W \times E \mid \mathcal{M}, w \models pre(e)\}$;
- $\sim'_i = \{((w, e), (w', e')) \in W' \times W' \mid w \sim_i w' \text{ and } e \sim_i e'\}$;
- $V'(p) = \{(w, e) \in W' \mid \mathit{eff}(e) \models p \text{ or } (\mathcal{M}, w \models p \text{ and } \mathit{eff}(e) \not\models \neg p)\}$;
- $W'_d = \{(w, e) \in W' \mid w \in W_d \text{ and } e \in E_d\}$.

$a = (\mathcal{E}, E_d)$ is applicable in $s = (\mathcal{M}, W_d)$ if for all $w \in W_d$ there is an event $e \in E_d$ so that $(\mathcal{M}, w) \models pre(e)$.

3.2 Planning tasks

A planning task $\Pi = \langle s_0, A, \omega, \gamma \rangle$ consists of a global state s_0 called the *initial state*; a finite set of actions A; an owner function $\omega : A \to \mathcal{A}$; and a *goal formula* $\gamma \in \mathcal{L}_{KC}$. We require that each $a \in A$ is local for $\omega(a)$.

Consider the planning task from the beginning. For simplicity, in this example there is only one player and the lever can only be pulled once. The planning task $\langle s_0, \{a_1\}, \omega, p \rangle$ consists of the initial state $s_0 = \underset{\neg p}{\odot}$ with the lever being in the upright position. The action $a_1 = \underset{e_1 : \langle \top, p \rangle}{\odot}$ has the owner $\omega(a_1) = 1$ (player 1). Everything is fully observable for the agent. The intuitive solution should prescribe the action a_1 to agent 1, pulling the lever to the right.

$$\underset{w_1 : \neg p}{\odot} \quad \otimes \quad \underset{e_1 : \langle \top, p \rangle}{\odot} \quad = \quad \underset{(w_1, e_1) : p}{\odot}$$

A policy π for $\Pi = \langle s_0, A, \omega, \gamma \rangle$ is a partial mapping $\pi : S^{gl} \hookrightarrow \mathcal{P}(A)$ such that :

1. Applicability

   We require actions to be applicable in all states they are assigned to:

   for all $a \in S^{gl}, a \in \pi(s) : a$ is applicable in s.

2. Uniformity

   If the policy π prescribes some action a to agent i in state s and agent i cannot distinguish s from some other state t, then π has to prescribe the same action

a for i in t as well:
for all $s, t \in S^{gl}$ such that $s^{\omega(a)} = t^{\omega(a)}, a \in \pi(s) : a \in \pi(t)$

3. Determinism
   We require π to be unambiguous for all agents in the sense that in each state s where an agent i is supposed to act according to π, π will always prescribe the same action for agent i.

The properties uniformity and applicability together imply knowledge of preconditions, the property that in each state, an agent who is supposed to perform a particular action must also know that the action is applicable in that state.

We also must allow policies to sometimes prescribe multiple actions of different owners to the same state. This is because the set of indistinguishable states can differ between the agents. To characterize the different outcomes of agents acting according to a common policy, we define the notion of policy executions.

An execution of a policy π from a global state s_0 is a maximal (finite or infinite) sequence of alternating global states and actions $(s_0, a_1, s_1, a_2, s_2, ...)$, such that for all $m \leq 0$

1. $a_{m+1} \in \pi(s_m)$ and

2. $s_{m+1} \in Globals(s_m \otimes a_{m+1})$

An execution is called successful for a planning task $\Pi = \langle s_0, A, \omega, \gamma \rangle$, if it is a finite execution $(s_0, a_1, s_1, ..., a_n, s_n)$ such that $s_n \models \gamma$.

(TODO: Geht das hier etwas schöner?) We now want to restrict our focus to policies that are guaranteed to achieve the goal after a finite number of steps. More formally, all of their executions must be successful. As in nondeterministic planning, such policies are called strong (Cimatti et al. 2003 [4]) **(TODO: Quelle lesen)**.

For a planning task $\Pi = \langle s_0, A, \omega, \gamma \rangle$, a policy π is called strong if $s_0 \in \mathrm{Dom}(\pi) \cup \{s \in S^{gl} \mid s \models \gamma\}$ and for each $s \in \mathrm{Dom}(\pi)$, any extension of π from s is successful for Π. A planning task is called solvable if a strong policy for Π exists. For $i \in \mathcal{A}$, we call a policy i-strong if it is strong and $Globals(s_0^i) \subseteq \mathrm{Dom}(\pi) \cup \{s \in S^{gl} \mid s \models \gamma\}$.

When a policy is i-strong it means that the policy is strong and defined on all the global states that agent i cannot indistinguish between. It follows directly from the definition that any execution of an i-strong policy from any of those initially indistinguishable states will be successful. So if agent i comes up with an i-strong policy, agent i knows the policy to be successful.

Sometimes the agents cannot coordinate their plans but rather have to come up with plans individually. These plans can differ a lot, the agents could have different reasoning capabilities, have non-uniform knowledge of the initial state and of action outcomes. For this reason we will define a policy profile for a planning task Π to be a family $(\pi_i)_{i \in \mathcal{A}}$ where each π_i is a policy for Π. We assume actions to be instantaneous and executed asynchronously. This leads to the following generalization:

An execution of a policy profile $(\pi_i)_{i \in \mathcal{A}}$ is a maximal (finite or infinite) sequence of alternating global states and actions $(s_0, a_1, s_1, ...)$, such that for all $m \leq 0$,

1. $a_{m+1} \in \pi_i(s_m)$ where $i = \omega(a_{m+1})$

   Note here the source of nondeterminism as a result from the possibility of multiple policies prescribing actions for their respective agents.

2. $s_{m+1} \in Globals(s_m \otimes a_{m+1})$

   Here the source of nondeterminism is from the possibility of nondeterministic action outcomes.

If all agents have one strong policy in common which all of them follow, then at execution time, the goal is guaranteed to be eventually reached. If, however, each agent acts on its individual strong policy, then the incompatibility of the individual policies may prevent the agents from reaching the goal, even tough each individual policy is strong.

4 The tokenized approach

Lets go back to the example from the beginning. The problem was that both agents a and b wanted to pull the lever to their own goal which results in infinite executions. This problem can be eliminated by introducing a token. With a token, only the player that has the token gets to execute an action. If the agent is done with their own actions, then they can pass the token on to the next player.

4.1 Infinite executions to finite executions

Infinite executions appear in the asynchronous executions order in which no token is used.

(EXTEND: einleitender Satz) We are now going to describe a function that takes a regular planning task and tokenize that task. The goal with the tokens is that only one player gets to make a move at a time.

Given a regular planning task $\Pi = \langle s_0, A, \omega, \gamma \rangle$, the function *tokenize* will transform the regular planning task into a tokenized planning task so that for all $a \in A$: if $a = \langle pre, \mathit{eff} \rangle$, then $tokenize(a) = \langle pre \wedge has(\omega(a), token), \mathit{eff} \rangle$.

Further we define an action $giveToken^{ij} = \langle has(i, token), \neg has(i, token) \wedge has(j, token) \rangle$ for all $i, j \in \mathcal{A}$.

Then $A^{Token} = \{tokenize(a) | a \in A\} \cup \{giveToken^{ij} | i, j \in \mathcal{A}, i \neq j\}$.

Moreover: $\omega^{Token}(tokenize(a)) = \omega(a)$ for all $a \in A$, and $\omega^{Token}(giveToken^{ij}) = i$

for all $i, j \in \mathcal{A}$.

Then $\Pi^{\text{Token}} = \langle s_0, A^{\text{Token}}, \omega^{\text{Token}}, \gamma \rangle$.

(EXTEND: hier auf die verschiedenen Token Typen eingehen)

(EXTEND: überleitender Satz)

Proposition 1. *Under the condition of optimal plans one can prevent the appearance of infinite executions in solvable games with asynchronous execution order with the introduction of a token based execution order.*

proof sketch. The game is finished when the agent that has the token reaches a goal state. When an agent that has a plan with the subjective cost of $n + m, m \leq 1$, that agent will start executing that plan and if needed, hand over the token to the next player. The agent will always decrease the subjective cost to n because handing over the token will also decrease the subjective cost. Because every agent decreases the subjective cost, the game is executable in infinite executions. □

4.2 The prevention of deadlocks

A deadlock for a policy profile $(\pi_i)_{i \in \mathcal{A}}$ is a global state such that

1. s is not a goal state

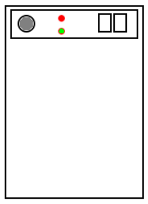
   Something still needs to be done

2. $s \in \text{Dom}(\pi_i)$ for some $i \in \mathcal{A}$

   Someone wants something to be done

3. $\omega(a) \neq i$ for all $i \in \mathcal{A}$ and $a \in \pi_i(s)$

   Nothing will be done because of incompatible individual policies



This can be seen in the following example: The two agents from before, Anne and Bill have to empty out the dishwasher. They each have a preference against doing this, since they both spend time (costs) to do this. **(EXTEND: hier vielleicht formal noch mal darstellen?)** In this example you can see that each agent expects the other agent to act, therefore no agent will act.

Up to this point, the token has given the player that has it the right to perform an action, a right that none of the other players have. But tokens could also force a player to perform an action.

Consider the definition from before with some changes marked in color:
Given a regular planning task $\Pi = \langle s_0, A, \omega, \gamma \rangle$, the function *tokenize* will transform the regular planning task into a tokenized planning task so that for all $a \in A$:
if $a = \langle pre, eff \rangle$, then $tokenize(a) = \langle pre \wedge has(\omega(a), token), eff \wedge doneAction(a) \rangle$
Former we define an Action $giveToken^{ij} = \langle has(i, token) \wedge doneAction(i), \neg has(i, token) \wedge has(j, token) \wedge \neg doneAction(i) \rangle$ for all $i, j \in \mathcal{A}$
Then $A^{Token} = \{tokenize(a) | a \in A\} \cup \{giveToken^{ij} | i, j \in \mathcal{A}, i \neq j\}$
Moreover: $\omega^{Token}(tokenize(a)) = \omega(a)$ for all $a \in A$, and $\omega^{Token}(giveToken^{ij}) = i$ for all $i, j \in \mathcal{A}$.
Then $\Pi^{\text{Token}} = \langle s_0, A^{\text{Token}}, \omega^{\text{Token}}, \gamma \rangle$

The changes imply that each agent can only pass on the token when that agent has performed an action.

Proposition 2. *Under the condition of optimal plans one can prevent the appearance of deadlocks in solvable games with asynchronous execution order with the introduction of a token based execution order.*

proof sketch. Before any player can give away the token, that player has to perform an action. If a player that has found a plan gets the token, that agent first has to do an action. This contradicts the definition of a deadlock. □

A deadlock is different from a dead end. In a dead end, none of the agents' policies prescribe an action, not even for another agent. In the definition (2) above it becomes obvious that these are two different things.

The problem with the tokens is the allocation of the token in the beginning. Each allocation type brings advantages, but also has some disadvantages. Lets start with the straightforward allocation we used up to now.

4.3 Asynchronous execution order

The first execution order is seemingly random. Some undefined agent has the token in the beginning. The advantage is that you do not have to define anything in the beginning, but this is also a disadvantage, since this token is defined, but the agent that has it in the beginning is not.

There are three other ways to introduce a token to this game.

1. Table token - the token is lying on a table and one of the agents can take the token in the beginning.
   The disadvantage becomes clear in the example with the dishwasher. No agent would take the token.

2. give token - in the specification of the game it is also specified which agent will have the token in the beginning.
   The problem with this introduction is that in every new game, this has to be written in the definition of the game. In order for the game to be efficient, it should be given to a player who has found a plan.

3. random token - the token is given to a random agent in the beginning. If that agent can not preform any action it can pass the token to a player who can.
   An agent who knows nothing and has no action will prevent the game from ever reaching a goal state.

Each version has its own drawbacks. In every game, you have to know the occurring problem beforehand to know which token allocation is efficient.

5 Conclusion

In conclusion, we can see that this approach solves the problem of the infinite executions, which other approaches do not solve. This approach also solves the problems that other approaches do solve, like deadlocks.

We can see that this execution order solves some of the problems that are not solved byt he other execution orders.

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I would like to thank my advisers the most. Without the two of them and their regular meetings, this thesis would not have been possible. Thank you for guiding me and helping me with the mathematical side of the writing and making sure that i present something each week.

ToDo Counters

To Dos: 3;   1, 2, 3

Parts to extend: 5;   1, 2, 3, 4, 5

Draft parts: 0;

Literaturverzeichnis

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