Bachelor Thesis

How does a token based order compare to the asynchronous 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.

Contents

1 Introduction

How would a perfect execution order look?

(TODO: What is an execution order?) (TODO: Who are the agents?)

This thesis is trying to answer that question by looking at the different execution orders. In other pieces of writing **(TODO: which?)** about epistemic planning the execution order is often unspecified, called an asynchronous execution order. This is easier to describe mathematically, but it also has some drawbacks. We are now going to have a look at the different execution orders, especially at the token based execution order.

The field of epistemic dynamic logic is relatively young. It started with the work from Plaza (1989) [1] about "Logics of public communications". Epistemic planning is taking regular planning task 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 only a very simplified model of the real world. In the real world, agents often have only little knowledge and can therefore make only limited calculations and beliefs 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.

There are multiple ways this research could be used in the future, in the real world. One example is in autonomous driving. Two cars are standing across from each other

on a bridge, only one car can pass. This problem could be solved with tokens.

“Many applications, such as robotic warehouses, must coordinate a large number of agents simultaneously to carry out their specific tasks.” This problem is usually described as the multi-agent path finding problem.

The thought of researching if a different order solves some problems is also done in multi agent path finding problems. Here, the problem gets more complex the more agents there are and it is very similar to the DEL approach.

This work is structured as follows: First, we are going to highlight the related work to this thesis. Then, we are going to introduce the mathematical background, dynamic epistemic logic (DEL). This logic is explained using a specific example, introduced in the beginning. Finally we are going to present the research of this thesis.

2 Related Work

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

This thesis is building up from the work of Bolander et al (2018) [2]. They investigated how a lazy agent, who had a preference against doing its own actions, compares to eager agents in planning problems. **(EXTEND: What did they find out?) (EXTEND: How is this different than my work? How does my work build up from their work?)**

DEL Papiere, Baltag und Moss implicit coordination

distributed systems, verteilte systeme $->$ vor allem Tokens

Tokens have also made an appearance in distributed systems **(TODO: cite)**. A distributed systems is a system where the components of the system are located apart from each other but they still have to communicate and coordinate their actions to achieve a common goal. This makes that field face some similar problems like the coordination of actions, the concurrency of the agents and the in-transparency. The field also needs scalable solutions.

In this field **(TODO: specify the field again)**, there are a few load balancing algorithms that try to equally distribute a task among several agents. Ray et al. (2012) [3] analyzed the different existing load balancing algorithms like token routing, round robin, randomized, Central queuing and Connection mechanism.
Another use case in this field is the restictional use of a mutual resource that can

only have a small number of users at a time. This can be achieved by using a token queue and a token semaphore, as from Makki et al. (1992) [4]

3 Background

Imagine the following game between two players, Anne and Bill. It involves a lever placed in between them. The lever is upright in the middle position and has five 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. Anne does not know Bill has a goal on his side, and Bill does not know Anne has a goal on her side. This can be seen in figure 1.

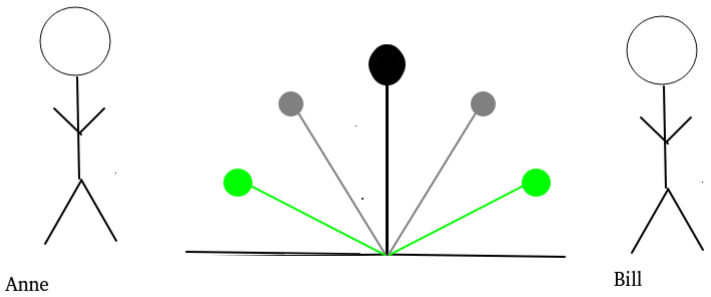


Figure 1: Visualization of the example

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?

3.1 Dynamic Epistemic Logic

In the following we will define and explain the core concepts of the Dynamic Epistemic Logic (DEL). DEL is a specific mathematical language used as the framework of this thesis.

The definitions are taken from the "Better eager than lazy" (2018) [2] paper, the "A gentle introduction to DEL" (2017) [5] and the book "Dynamic epistemic logic" from Ditmarsch [6].

Let $\mathcal{A}$ be a finite set of agents, from the example above this would be $\mathcal{A} = \{\text{Anne}, \text{Bill}\}$. 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:

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

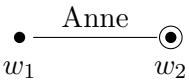
with $p \in \mathcal{P}$ and $i \in \mathcal{A}$. $\top$ describes φ as being true, $\bot$ as false. $K_i\varphi$ reads as "Agent i knows φ". $C\varphi$ reads as "it is common knowledge that φ ". From the example before, the two agents, a (Anne) and b (Bill) have two goal positions, goal p (lever to 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. Let w_1 be the world where just the lever to the left is a goal and w_2 be the world where the goal is the lever to the left or to the right, then $w_1 \sim_a w_2$.



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.

From the example above, Anne has the local state $(\mathcal{M}, \{w_1, w_2\})$

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

$\varphi, \psi \in \mathcal{L}_{\mathrm{KC}}(P, \mathcal{A})$, we define truth as follows:

$$
\begin{array}{lll}
(\mathcal{M}, W_d) \models \varphi & \text{iff} & (\mathcal{M}, w) \models \varphi \text{ for all } w \in W_d \\
(\mathcal{M}, w) \models p & \text{iff} & w \in V(p) \\
(\mathcal{M}, w) \models \neg\varphi & \text{iff} & (\mathcal{M}, w) \not\models \varphi \\
(\mathcal{M}, w) \models \varphi \wedge \psi & \text{iff} & (\mathcal{M}, w) \models \varphi \text{ and } (\mathcal{M}, w) \models \psi \\
(\mathcal{M}, w) \models K_i\varphi & \text{iff} & (\mathcal{M}, v) \models \varphi \text{ for all } v \sim_i w \\
(\mathcal{M}, w) \models C\varphi & \text{iff} & (\mathcal{M}, v) \models \varphi \text{ for all } v \sim^* w \\
(\mathcal{M}, w) \models \top & & \text{always} \\
(\mathcal{M}, w) \models \bot & & \text{never}
\end{array}
$$

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

Using Anne and Bill as an Example, Anne only knows p is true. She cannot distinguish between p, q and $p, \neg q$. Bill only knows q is true, he 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.

$$
s = \quad \underset{w_1 : p, \neg q}{\bullet} \overset{\text{Anne}}{\text{———}} \underset{w_2 : p, q}{\circledcirc} \overset{\text{Bill}}{\text{———}} \underset{w_3 : \neg p, q}{\bullet}
$$

We have the designated world (M, w_2). THis designated world says nothing about the knowledge of Anne. She still cannot destinguish between if q is true or not. $(M, w_2) \models \neg K_a q \vee \neg K_a \neg q$. Performing a perspective sift on $s = (M, w_2)$ for Anne is $(M, w_2)^{\text{Anne}} = (M, \{w_1, w_2\})$. This perspective shift gives us $(M, \{w_1, w_2\}) \not\models q$ and $(M, \{w_1, w_2\}) \not\models \neg q$.

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; $pre : E \to \mathcal{L}_{KC}$ assigns a precondition to each event; and $\mathit{eff} : E \to \mathcal{L}_{KC}$ 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 $\mathcal{E} = \langle pre(e), \mathit{eff}(e)\rangle$.

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 :

- a new world, emerging from the old world with all executable actions
  $W' = \{(w, e) \in W \times E \mid \mathcal{M}, w \models pre(e)\}$;

- new worlds are indistinguishable if the old world and the events are indistinguishable
  $\sim'_i = \{((w, e), (w', e')) \in W' \times W' \mid w \sim_i w' \text{ and } e \sim_i e'\}$;

- all propositions become true if the proportions occurred in the effect of the event or the proposition was positive in the world bevore and did not appear negative in the effect
  $V'(p) = \{(w, e) \in W' \mid \mathit{eff}(e) \models p \text{ or } (\mathcal{M}, w \models p \text{ and } \mathit{eff}(e) \not\models \neg p)\}$;

- designated worlds emerge from designated predecessor worlds and designated events
  $W'_d = \{(w, e) \in W' \mid w \in W_d \text{ and } e \in E_d\}$.

$a = (\mathcal{E}, E_d)$ 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 $(\mathcal{M}, w) \models pre(e)$.

(TODO: Announcment action)

(TODO: Sensing Action)

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* $\gamma \in \mathcal{L}_{KC}$.

Consider a verson of the lever problem from before. 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 $s_0 = \underset{\neg p}{\circledcirc}$ with the lever being in the upright position. The action $a_1 = \underset{e_1 : \langle \top, p \rangle}{\circledcirc}$ 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.

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

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 $s^{\omega(a)} = t^{\omega(a)}, a \in \pi(s) : a \in \pi(t)$

   (TODO: Counterexample with queen)

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 $s_n \models \gamma$.

(EXTEND: Example: Anna lets Bill pull the lever to the right. Globally this makes sense, since that is Bills goal. But individually, this makes no sense at all because Anne doesent know Bills goal.)

(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 [7]) **(TODO: Quelle lesen)**.

For a planning task $\Pi = \langle s_0, A, \omega, \gamma \rangle$, a policy π is called strong if $s_0 \in \text{Dom}(\pi) \cup \{s \in S^{gl} \mid s \models \gamma\}$ and for each $s \in \text{Dom}(\pi)$, any execution 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 $Globals(s_0^i) \subseteq \text{Dom}(\pi) \cup \{s \in S^{gl} \mid s \models \gamma\}$.

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 ofthen have different knowledge about the states, the actions and therefore the 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. $s_{m+1} \in \mathit{Globals}(s_m \otimes a_{m+1})$

   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

In 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.

There are different ways to model the token. We are going to start with adding an action that lets one agent hand the token to the next agent. Modeling the token in the beginning of the planning task is a little bit different, since there are multiple ways the token can be introduced to the agents.

There are three other ways to introduce a token to this game. **(TODO: Du nimmst bisher keine Referenz zum Kapitel davor. Wuerde das bedeuten, dass man das "Token nehmen" und "Token abgeben" als Aktion in den Planungsalgorithmus einfuehren muss. Dann wuerde ich das hier schreiben.)**

1. “Table token” - the token is lying on a table and one of the agents can take the token in the beginning.
   The disadvantage is that maybe 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.
   One disadvantage would be that an agent who knows nothing and has no action will prevent the game from ever reaching a goal state.

There are also two different types of tokens. The first type of token can be easily passed from one agent to the next without any restriction. This token makes sure that no unwanted agent performs an action that could lead to a worse plan than before. the second type of token forces an agent to perform an action before handing the token to the next agent. This type of token makes sure that the token is not just passed between the agents, it makes sure the agents contribute to reaching a goal state.

4.1 Infinite executions to finite executions

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 $tokenize(a) = \langle pre \wedge hasToken_{\omega(a)}, \mathit{eff} \rangle$.
Further we define an action $giveToken^{ij} = \langle hasToken_i, \neg hasToken_i \wedge hasToken_j \rangle$ for all $i, j \in \mathcal{A}$ with $i \neq j$.
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 $i, j \in \mathcal{A}$.

With j depending on the way the token should be introduced to the token:

1. Table Token: The first agent to take the token off the table. Here we need a new action that, if no player has the token, one player can take the token. $takeToken_j = \langle \neg hasToken_i \forall i \in \mathcal{A}, hasToken_j \rangle \forall i, j \in \mathcal{A}$ with $\omega(takeToken_j) = j$. Then the game starts with no player having the token $s_0^{TableToken} = s_0 \cup \neg hasToken_i$.

2. give Token: a specified agent to be determined by the game maker. We can model this by having $s_0^{giveToken}(j)$ have the variable j, the agent that is supposed to have the token in the beginning. $s_0^{giveToken}(j) = s_0 \cup \{\neg hasToken_i | i \in \mathcal{A} \backslash j\} \cup hasToken_j$

3. random Token: a random agent to model this we need to define some other things first. $w_{randomToken} = \{w_i | w \in W, i \in \mathcal{A}\}$
   $w^i \sim v^i$ iff $w \sim v$ and $i = j$
   $V(p) = \{w' | w \in V(p), i \in \mathcal{A}\}$
   $w_d = \{w' | w \in W_d, i \in \mathcal{A}\}$

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

The action *giveToken* can have different costs. One option would be to have the the action cost nothing, then the overall cost of the plan would not change. THe problem with this is it does not prevent the agents from just passing the token around without a goal. The other option is that the action has the cost 1, then the agents will not just pass the token around,, they will want to do all possible actions themselves before handing the token to the next agent.

In searching for the optimal plan the search tree can have a smaller width, because the amount of agents that could perform the next action is limited. Therefore the

search tree will probably have a deeper depth, because the action handing off the token will also have to be modeld. This could be researched in the future.

(EXTEND: Lever example with tokens)

Given this formalization, we can now show that we can stop infinite executions from happening in planning tasks by transforming the regular planning task into a tokenized planning task.

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 execution is finished when an agent that has the token does not want to do anything.
When an agent i that has a plan gets handed the token, that player has three possible actions:

1. keep the token and execute an action a, which will lower the subjective costs of the remaining policy by at least 1.
   $s \overset{a}{\mapsto} s'$
   $c_i(s') \leq c_i(s) - 1$

2. give the token to another agent. In order to pass on the token, the agent that has found the plan would have already performed a perspective shift for the next agent in order to check if the next agent could also find that plan and calculated the subjective cost of the remaining plan. The agent that receives the token will always execute that plan or find a better plan and execute the better plan.
   There are two possible outcomes for the next agent:

a) The next agent (j) has found a plan with an action a'.
   $a = passToken^{ij}$
   $a' \in \pi_i(s')$
   $c_j(s')leqc_i(s) - 1$

b) The next agent does not want to perform an action. This case will eventually be reached because the subjective costs will never be able to be below zero.
   If $c_j(s) = 0$, agent j would not act.

3. Do nothing.

Every agent that will get the token in the plan will either decrease the subjective cost of the policy or stop the execution. Because every agent in the execution 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. $s \in \mathrm{Dom}(\pi_i)$ 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

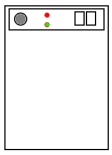


Figure 2: Dishwasher

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. In this example you can see that each agent expects the other agent to act, therefore no agent will act.

Let initially, in s_0, the dishwasher be full. Agent 1 has an action a_1 and Agent 2 has an action a_2 that can both be applied in s_0 and have the effect that has the effect that the dishwasher is empty afterwards. Then the policies $\pi_1 = \{s_0 \overset{a_2}{\longmapsto} emptyDishwasher\}$ and $\pi_2 = \{s_0 \overset{a_1}{\longmapsto} emptyDishwasher\}$ are both i-strong policies.

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-force* 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 $tokenize{-}force(a) = \langle pre \wedge hasToken_{\omega(a)}, eff \wedge doneAction_{\omega(a)} \rangle$
Former we define an Action $giveToken^{ij} = \langle hasToken_i \wedge doneAction_i, \neg hasToken_i \wedge hasToken_j \wedge \neg doneAction_i \rangle$ 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: $\omega^{Token}(tokenize{-}force(a)) = \omega(a)$ for all $a \in A$, and $\omega^{Token}(giveToken^{ij}) = i$ for all $i, j \in \mathcal{A}$.
$s_0^{Token} = s_0 \cup \{\neg hasToken_i | i \in \mathcal{A} \backslash j\} \cup hasToken_j \cup \{\neg doneAction_i | i \in \mathcal{A}\}$ with $j \in \mathcal{A}, |j| = 1$
With j depending on the way the token should be introduced to the token:

1. Table Token: The first agent to take the token off the table.

2. give Token: a specified agent to be determined by the game maker

3. random Token: a random agent

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

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

This new token version also solves the infinite execution problem.

Proposition 2. *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 force 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 gets handed the token, that player first has to perform an action, thereby lowering the subjective cost, and then that player has two possible actions:

1. keep the token and execute another action, which will lower the subjective costs of the remaining policy profile or

2. give the token to the next player. in order to pass on the token the player that has found the plan would have already performed a perspective shift for the next player, in order to check if the next player could also find that plan and calculated the subjective cost of the remaining plan. The player that receives the token will always execute that plan or find a better plan and execute the better. plan.

Every agent that will get the token in the plan will decrease the subjective cost of the policy profile, and because every agent decreases the subjective cost, the game is executable in infinite executions. □

Proposition 3. *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 force token based execution order with the exception of the table token introduction of the token.*

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. □

The table token introduction of the token does not prevent deadlocks because in this case, no agent would take the token off the table, which causes a deadlock.

Proposition 4. *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 with the exception of the table token introduction of the token, as long as the giveToken action costs at least 1.*

proof sketch. In order to have a policy profile with minimal costs, the agent will have to minimize the amount of giveToken actions in the policy profile. Therefore the agent will always perform an action them self instead of passing the token away, if possible. Because the agents have a common individual policy of keeping the subjective costs minimal, 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. **(TODO: is this really needed? It looks unmotivated)**

5 Conclusion

We looked at how the two different token orders solved the two main problems: Deadlocks and infinite executions. We discussed that there are three different ways to introduce a token and all except the table token solve both problems. The table token does not solve the deadlock problem because there is the possibility that no agent takes the token off the table. This is illustrated in the following table:

	table token	random token	give token
empower token	solves infinite executions doesn't solve deadlocks	solves infinite executions solves deadlocks	solves infinite executions solves deadlocks
force action token	solves infinite executions doesn't solve deadlocks	solves infinite executions solves deadlocks	solves infinite executions solves deadlocks

This means that there are positive results with the introduction of a token based order. In every case, if an agent that has found a plan gets the token, the goal will be reached in a finite number of steps.

We do not need to enforce agents to be eager to avoid deadlocks if we use the tokens with costs. **(TODO: vorne rein schreiben.)**

Eager agents können weggelassen werden weil man mit Kosten gleich 1 die deadlocks und die infinite executions in den meisten fällen lösen kann. Mit den force tokens können die lazy agenten zu sachen gezwungen werden, es ist also egal ob die agents eager, overeager oder lazy sind.

For future work, the way the token changes the search of a plan should be researched. With Tokens, the search tree of a plan might have a smaller width but also a deeper

depth. **(TODO: This is written in the text)**

There could also be future research in researching the fairness of the tokens. How do the tokens get passed from player to player and if that is fair.

Another field of research for the future could be impatient players and the table token execution order. An impatient player will wait for the other player to take the token first, but only for a limited amount of time. For this we would need to extend the formalism since we cannot model time or a waiting agent explicitly.

ToDo Counters

To Dos: 14; 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14

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

Draft parts: 0;

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