Many-dimensional Modal Logic of Tense and Temporal Interval and its Decidability

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Abstract— Linear tense logics are widely accepted for structural temporal representation, where the basic K_T has two modal operators G and H, each of which represents the future and the past, respectively. On the other hand, the temporal interval relations arranged by Allen have long been the standard of natural language semantics, though it still lacks the modal-logical foundation. Van Benthem [10] proposed $\Box^{up}$ and $\Box_{down}$ in regard to the accessibility to overlapping intervals and subintervals, respectively; however, the logical feature of the modality has not well studied. In this study, we propose a many-dimensional logic including the conventional tense logic, together with such interval accessibility, and show its decidability.

Keywords— decidability, many-dimensional modal logic, sequent system, temporal logic.

I. Introduction

In the field of artificial intelligence, temporal logics are widely utilized for structural temporal representations. Thus far, many linguists and computer scientists have proposed the temporal relations in occurrences. In [10], [17], [18], for the temporal precedence relations and the temporal inclusion relations, authors have shown the hereditary properties. In this paper, by representing the temporal relations as the modality, we propose a many-dimensional logic of the tense and interval logic. We show our logic represents the temporal aspect of occurrences. Additionally, we introduce a sequent system for our logic, and show the concrete decision procedure and its decidability.

In the following section, we propose a formalization of the temporal relations, and define the syntax and Kripke semantics for our tense interval logic. In Section III, we introduce a sequent system for our logic and show a proof-search procedure. In the final section, we discuss some branching points of our theory and summarize our contribution.

II. Tense interval logics

The prime distinction of states of affairs, that is, *event* and *state*, is explained by the following *upward*/*downward* heredity [18]. "Anna found her purse between 4PM and 5PM" implies "Anna found it between 3:30PM and 5:30PM." Thus, if an instantaneous *event* is mentioned in an interval, then so is also in overlapping intervals; that is upward hereditary. On the contrary, "Beth was sleeping between 3:30PM and 5:30PM" implies "Beth was sleeping between 4PM and 5PM." Therefore, if a durative *state* is valid all through the interval, then so is also in its subintervals. This is said to be downward hereditary. We define the *inclusion* relation '$\subseteq$' between temporal extents, as well as the conventional *precedence* relation '$\prec$', and propose a many-dimensional logic with these two different accessibilities, regarding a temporal extent as a possible world.

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A. Syntax

Definition 1 (Signature): The language L_1 consists of the following vocabulary.

propositional variables:	p, q, r,$\cdots$
logical connectives:	$\neg$, $\vee$, $\wedge$, $\Rightarrow$
modal operators:	G, H, $\Box^{\uparrow}$, $\Box_{\downarrow}$

Parentheses and punctuation are added if necessary.

We use $\varphi, \psi, \chi, \cdots$ for formulae which are constructed inductively from propositional variables, logical connectives and modal operators in the usual way. Modal operators F, P, $\Diamond^{\uparrow}$, and $\Diamond_{\downarrow}$ are abbreviations of $\neg G \neg$, $\neg H \neg$, $\neg \Box^{\uparrow} \neg$, and $\neg \Box_{\downarrow} \neg$, respectively. Modal operators are interpreted in the following.

$G\varphi$	at all future time, φ
$H\varphi$	at all past time, φ
$\Box^{\uparrow}\varphi$	in all superintervals, φ
$\Box_{\downarrow}\varphi$	in all subintervals, φ

Hereafter, we abbreviate $\Box^{\uparrow}$ and $\Box_{\downarrow}$ to $\Box$ if they are commonly treated. Each of the minimal tense logic K_T and $K_\Box$ is defined to be the least *normal modal logic* containing each of the following axioms, respectively.

	K_T		$K_\Box$
(A_T1)	$G\varphi \Rightarrow GG\varphi$	$(A_\Box 1)$	$\Box\varphi \Rightarrow \Box\Box\varphi$
(A_T2)	$H\varphi \Rightarrow HH\varphi$	$(A_\Box 2)$	$\Box\varphi \Rightarrow \varphi$
(A_T3)	$\varphi \Rightarrow GP\varphi$		
(A_T4)	$\varphi \Rightarrow HF\varphi$		

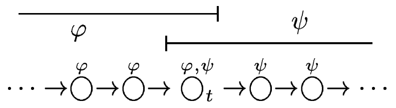
Optionally, the seriality of the interval ordering would be reflected by

$$(A_\Box 3)\ \ \Box\varphi \Rightarrow \neg\Box\neg\varphi.$$

In this paper, $K_\Box$ is axiomatized by the axioms $(A_\Box 1)$, $(A_\Box 2)$, and $(A_\Box 3)$. That is, we regard $K_\Box$ as the modal logic **S4**. Our logic $K_T + K_\Box$ is obtained by *fusion* of K_T and $K_\Box$. Now, let L_1 and L_2 be two modal logics. If L_1 is axiomatized by a set of axioms Ax_1 and L_2 is axiomatized by Ax_2, then the fusion $L_1 + L_2$ [1] of L_1 and L_2 is axiomatized by the union $Ax_1 \cup Ax_2$ [3].

[1] The fusion can be also denoted as $L_1 \otimes L_2$.

Our logic bears a resemblance to the conventional interval logics. Each possible world shows a feature of the temporal interval, however, unlike the conventional interval logic, our logic represents the $discrete$ [2] temporal relations by the accessibility of possible worlds. For example, our logic can represent an overlapping relation between φ and ψ as follows.



B. Kripke semantics

We introduce Kripke semantics for tense-interval logics. A Kripke model for our logic is a tuple $(W, R_T, R_\diamond, \Vdash)$, where W is a non-empty set, and R_T and $R_\diamond$ are binary relations on W, and $\Vdash$ is defined inductively as follows.

$(M1)$ $u \Vdash \varphi \wedge \psi$ *iff* $u \Vdash \varphi$ and $u \Vdash \psi$
$(M2)$ $u \Vdash \varphi \vee \psi$ *iff* $u \Vdash \varphi$ or $u \Vdash \psi$
$(M3)$ $u \Vdash \varphi \Rightarrow \psi$ *iff* $u \Vdash \varphi$ implies $u \Vdash \psi$
$(M4)$ $u \Vdash \neg\varphi$ *iff* $u \nVdash \varphi$
$(M5)$ $u \Vdash G\varphi$ *iff* $\forall v \in W$, uR_Tv implies $v \Vdash \varphi$
$(M6)$ $u \Vdash H\varphi$ *iff* $\forall v \in W$, vR_Tu implies $v \Vdash \varphi$
$(M7)$ $u \Vdash \Box^{\uparrow}\varphi$ *iff* $\forall v \in W$, $uR_\diamond v$ implies $v \Vdash \varphi$
$(M8)$ $u \Vdash \Box_{\downarrow}\varphi$ *iff* $\forall v \in W$, $vR_\diamond u$ implies $v \Vdash \varphi$

A formula φ is *true in model* $\mathcal{M}$=$(W, R_T, R_\diamond, \Vdash)$, denoted by $\mathcal{M} \models \varphi$, if $u \Vdash \varphi$ for every $u \in W$. Now, the following hold.

(1) $\mathcal{M} \models G\varphi \Rightarrow GG\varphi$ *iff* $\forall u, v, w(uR_Tv \wedge vR_Tw \to uR_Tw)$
(2) $\mathcal{M} \models H\varphi \Rightarrow HH\varphi$ *iff* $\forall u, v, w(wR_Tv \wedge vR_Tu \to wR_Tu)$
(3) $\mathcal{M} \models \varphi \Rightarrow GP\varphi$ *iff* $\forall u, v(uR_Tv \to vR_Tu)$
(4) $\mathcal{M} \models \varphi \Rightarrow HF\varphi$ *iff* $\forall u, v(vR_Tu \to uR_Tv)$
(5) $\mathcal{M} \models \Box\varphi \Rightarrow \neg\Box\neg\varphi$ *iff* $\forall u \exists v(uR_\diamond v)$
(6) $\mathcal{M} \models \Box\varphi \Rightarrow \Box\Box\varphi$ *iff* $\forall u, v, w(uR_\diamond v \wedge vR_\diamond w \to uR_\diamond w)$
(7) $\mathcal{M} \models \Box\varphi \Rightarrow \varphi$ *iff* $\forall u(uR_\diamond u)$

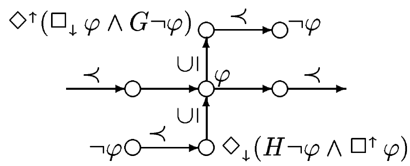
If R_T and $R_\diamond$ satisfy all of conditions from (1) to (7) for $\mathcal{M}$, $\mathcal{M}$ is called a $K_T + K_\Box$-model.

Now, we have the following proposition, constructing the canonical model[14] of our logic.

Proposition 1: Let $\mathcal{L}$ be $K_T + K_\Box$. $\forall\varphi$, $\varphi \notin \mathcal{L}$ *iff* there exists $\mathcal{L}-$model $\mathcal{M}$ such that $\mathcal{M} \not\models \varphi$.

C. Aspectual classification

A state and an event satisfy $\varphi \Rightarrow \Box_{\downarrow}\varphi$ and $\varphi \Rightarrow \Box^{\uparrow}\varphi$, respectively for the upward/downward heredity. For a state, we may hypothesize the starting/ending points by assuming a certain superinterval. Then, $\varphi \Rightarrow \Diamond^{\uparrow}\Box_{\downarrow}\varphi$, where $\Diamond^{\uparrow}$ denotes some possible world which includes the assumed starting/ending points. If we could clearly specify the starting point and the ending point, then we can claim $\varphi \Rightarrow \Diamond^{\uparrow}(H\neg\varphi \wedge \Box_{\downarrow}\varphi)$ and $\varphi \Rightarrow \Diamond^{\uparrow}(\Box_{\downarrow}\varphi \wedge G\neg\varphi)$, respectively. In the similar way, if we assume a minimal interval of an event, $\varphi \Rightarrow \Diamond_{\downarrow}\Box^{\uparrow}\varphi$, where $\Diamond_{\downarrow}$ denotes the subinterval including the instance of the event. As, $\varphi \Rightarrow \Diamond_{\downarrow}(H\neg\varphi \wedge \Box^{\uparrow}\varphi \wedge G\neg\varphi)$ represents the $achievement$ of the aspect class by Vendler[19], we can regard this formula as a representation of the $culmination$. We show some relations as follows.



III. Decidability

In this section, we introduce a sequent system for the tense-interval logic. We show the subformula property holds in our system, and thus are able to show the decidability. In the following, uppercase Greek letters, $\Gamma, \Delta, \Pi, \Sigma$ and Λ denote finite sets of formulae, and also Θ consists of at most one formula. And $\Box\Gamma$ denotes $\{\Box\varphi | \varphi \in \Gamma\}$ for $\Box \in \{\Box^{\uparrow}, \Box_{\downarrow}\}$. *Sub*$(\Gamma)$, Γ_*, and Δ^* denote $\bigcup\{Sub(\psi) | \psi \in \Gamma\}$, $\bigwedge\{\varphi | \varphi \in \Gamma\}$, and $\bigvee\{\varphi | \varphi \in \Delta\}$, respectively, where $Sub(\psi)$ denotes a set of all subformulae of φ. Any expression of the form $\Gamma \to \Delta$ is called a $sequent$, where $\to$ denotes a $derivation\ relation$. An $inference\ rule$ is of the form

$$\frac{S_1}{S} \quad or \quad \frac{S_2 \quad S_3}{S},$$

where S_1, S_2, S_3, and S are sequents. In the inference, S_1, S_2, and S_3 are called the $upper\ sequents$, and S the $lower\ sequent$.[3]

A. Sequent system for tense interval logic

The sequent system $G(K_T + K_\Box)$ is obtained from the sequent system $\mathbf{LK}$ for the classical propositional logic by adding the following four rules.

$$(\Box 1) \quad \frac{\varphi, \Sigma \to \Lambda}{\Box\varphi, \Sigma \to \Lambda} \qquad (\Box 2) \quad \frac{\Box\Sigma \to \varphi}{\Box\Sigma \to \Box\varphi}$$

$$(T1) \quad \frac{G\Sigma, \Sigma \to H\Lambda, H\Theta, \varphi}{G\Sigma \to H\Lambda, \Theta, G\varphi}$$

$$(T2) \quad \frac{H\Sigma, \Sigma \to G\Lambda, G\Theta, \varphi}{H\Sigma \to G\Lambda, \Theta, H\varphi}$$

Rule (T1) and (T2) are included in K_T. Since $K_\Box$ is the modal logic $\mathbf{S4}$, we introduced Rule $(\Box 1)$ and $(\Box 2)$.

[2]If the time axis is the $dense$, we can represent it by adding the axioms '$GG\varphi \Rightarrow G\varphi$' and '$HH\varphi \Rightarrow H\varphi$'[18].

[3]If a sequent S is provable in a system G, then it is often denoted by $G \vdash S$.

Proposition 2:
$\Gamma_* \Rightarrow \Delta^* \in K_T + K_\Box \quad \Leftrightarrow \quad G(K_T + K_\Box) \vdash \Gamma \to \Delta.$

The sequent system $G(K_T + K_\Box)$, however, lacks the cut-elimination property, so that subformula property does not hold. For example, a sequent $\varphi \to G\neg H\neg\varphi$ is not provable without the cut rule[1]. Takano[12] introduced the restricted cut rule (AC) and showed that those with the subformula property become provable in the revised sequent system. So, for $G(K_T + K_\Box)$, by applying the restricted cut rule, we introduce $G^-(K_T + K_\Box)$ as follows.

$$(AC) \quad \frac{\Sigma \to \Lambda, \varphi \qquad \varphi, \Pi \to \Theta}{\Sigma, \Pi \to \Lambda, \Theta} \quad \text{where } \varphi \in Sub(\Sigma \cup \Lambda \cup \Pi \cup \Theta)$$

$$(T1)' \quad \frac{G\Sigma, \Sigma \to H\Lambda, H\Theta, \varphi}{G\Sigma \to H\Lambda, \Theta, G\varphi} \quad \text{where } H\Theta \subseteq Sub(\Sigma \cup \Lambda \cup \{\varphi\})$$

$$(T2)' \quad \frac{H\Sigma, \Sigma \to G\Lambda, G\Theta, \varphi}{H\Sigma \to G\Lambda, \Theta, H\varphi} \quad \text{where } G\Theta \subseteq Sub(\Sigma \cup \Lambda \cup \{\varphi\})$$

In (AC), $(T1)'$ and $(T2)'$, we can easily see that every formula occurring in the upper sequents consists of subformulae of formulae in the lower sequent. Maruyama et al. showed the completeness theorem of the restricted system in [1], and thus we can prove the completeness theorem of our system in the same way. That is, we have the following theorem.

Theorem 1: If a sequent $\Gamma \to \Delta$ is not provable in $G^-(K_T + K_\Box)$, then there is a finite $K_T + K_\Box$-model $\mathcal{M}$ such that $\mathcal{M} \not\models \Gamma_* \Rightarrow \Delta^*$.

Here, we summarize the above results as follows.

$\Gamma_* \Rightarrow \Delta^* \notin \mathcal{L}$	$\Leftrightarrow$	$M_\mathcal{L} \not\models \Gamma_* \Rightarrow \Delta^*$
$\Updownarrow$Prop.2	Prop.1	
$G(\mathcal{L}) \not\vdash \Gamma \Rightarrow \Delta$		$\Uparrow$
$\Downarrow$[12]	Theorem1	
$G^-(\mathcal{L}) \not\vdash \Gamma \Rightarrow \Delta$	$\Rightarrow$	$FM_\mathcal{L} \not\models \Gamma_* \Rightarrow \Delta^*$

Where $\mathcal{L}$, $M_\mathcal{L}$, and $FM_\mathcal{L}$ denote $K_T + K_\Box$, a model of $\mathcal{L}$, and a finite model of $\mathcal{L}$, respectively. That is, the restricted systems $G^-(\mathcal{L})$ is equivalent to $G(\mathcal{L})$.

Corollary 1: If $\varphi \notin K_T + K_\Box$, then there exists a finite $K_T + K_\Box$-model $\mathcal{M}$ such that $\mathcal{M} \not\models \varphi$.

The decidability of $K_T + K_\Box$ follows Harrop's theorem[14].

Theorem 2: [Harrop] If a finitely axiomatizable logic has the finite model property, then it is decidable.

By [11], the fusions of modal logics with finite model property have the finite model property. Besides that, for complete modal logics L_1 and L_2 not containing $\bot$, the fusion $L_1 + L_2$ is decidable if both components L_1 and L_2 are decidable. The decision procedure by Harrop's theorem is extremely inefficient, and not feasible practically. But, if a logic has the finite model property, there exists a model which invalidates unprovable formulae. Therefore, we can expect that such formulae are found in the model efficiently. The decision procedure by using the restricted sequent system is more efficient procedure. We show a proof-search procedure for $K_T + K_\Box$ in the following section.

B. Proof-search procedure

A decision procedure for $K_T + K_\Box$ is a concrete finite procedure which decides whether a given formula is provable or not in a logic $K_T + K_\Box$. For $\Gamma \Rightarrow \Delta$, when the same formula appears only once in each of Γ and Δ, we call it *1-reduce*. If $\Gamma \Rightarrow \Delta$ is not 1-reduce, then we obtain a 1-reduce sequent by using contraction and exchange rules. So, it is enough to search a proof for 1-reduce sequents. Here, a reduced sequent which consists of formulae in *Sub*$(\Gamma \cup \Delta)$ is called a *suitable sequent*. Then, it is enough to search a proof which consists only of suitable sequents. Every proof can be transformed into the proof without any repetition of sequents. Here we call 'partially constructed proofs', *inference figure*. In the inference figure, each rule must be applied in a correct way, but the uppermost sequents are not necessarily the initial sequents. For each i, let $\mathcal{G}_i$ be the set of all the inference figures in which inference rules are applied at most $i-1$ times. Paying attention to these things, we can obtain the following procedure.

1) $\mathcal{G}_1$ is the singleton set consists only of $\Gamma \Rightarrow \Delta$. The figure of such a set is an inference figure.
2) Suppose that $\mathcal{G}_i$ is already defined.
   2.1 $\mathcal{G}_{i+1} := \mathcal{G}_i$.
   2.2 $\forall \mathcal{F} \in \mathcal{G}_i$, If $\exists \mathcal{I}$ such that $\mathcal{F}^\wedge = \mathcal{I}^\vee$ and $\mathcal{F}^\wedge \notin \{\mathcal{F}^\vee\}$, then $\mathcal{G}_{i+1} := \mathcal{G}_{i+1} \cup \mathcal{F}'$ such that $\mathcal{F}' - \mathcal{F} = \mathcal{I}^\wedge$.
3) If $\mathcal{G}_{i+1} = \mathcal{G}_i$, then output "$\Gamma \Rightarrow \Delta$ is not provable," and terminates.
4) If $\exists \mathcal{F}$ such that $\mathcal{F} \in \mathcal{G}_{i+1} - \mathcal{G}_i$ and $\mathcal{F}^\wedge = IS$, then output "$\Gamma \Rightarrow \Delta$ is provable" and terminates. Otherwise, go to step 2.

Where $\mathcal{F}^\wedge$, $\mathcal{F}^\vee$, $\mathcal{I}$, and IS denotes the uppermost sequent of $\mathcal{F}$, the lower sequents of $\mathcal{F}$, the inference rules, and the initial sequents, respectively. The above procedure demands the backtracking for the loop-checking by 2.2. So, a sequent system proves a bottom-up manner. Since the set of all the non-repetition inference figures which consist only of acceptable sequents is finite, and so there must exist a natural number j such that $\mathcal{G}_{j+1} = \mathcal{G}_j$. Therefore, the above procedure eventually terminates.

Example 1: We will consider the following formula.
$$\neg(\Box^\uparrow(G\varphi \wedge \varphi) \wedge (G\neg\varphi \wedge \neg\varphi))$$

Suppose that if P_1 is $\to \neg(\Box^\uparrow(G\varphi \wedge \varphi) \wedge (G\neg\varphi \wedge \neg\varphi))$, then $P_1 \in \mathcal{G}_1$.

f P_2 is $\dfrac{\Box^{\uparrow}(G\varphi \wedge \varphi) \wedge G\neg\varphi \wedge \neg\varphi \to}{P_1}$, then $P_2 \in \mathcal{G}_2$.

$$\vdots$$

If P_8 is $\dfrac{\Box^{\uparrow}(G\varphi \wedge \varphi), G\neg\varphi, \neg\varphi \to}{P_5}$, then $P_6 \in \mathcal{G}_6$.

If P_9 is $\dfrac{G\varphi \wedge \varphi, G\neg\varphi, \neg\varphi \to}{P_6}$, then $P_7 \in \mathcal{G}_7$.

Thus, we have the following proof.

$$\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\varphi \to \varphi}{\neg\varphi, \varphi \to}\,(\neg \Rightarrow)}{\varphi, \neg\varphi \to}\,(exchange)}{G\varphi \wedge \varphi, \neg\varphi \to}\,(\wedge \Rightarrow)}{G\varphi \wedge \varphi, G\neg\varphi, \neg\varphi \to}\,(weakning)}{\Box^{\uparrow}(G\varphi \wedge \varphi), G\neg\varphi, \neg\varphi \to}\,(\Box 1)}{\Box^{\uparrow}(G\varphi \wedge \varphi) \wedge (G\neg\varphi \wedge \neg\varphi) \to}}{\to \neg(\Box^{\uparrow}(G\varphi \wedge \varphi) \wedge (G\neg\varphi \wedge \neg\varphi))}\,(\neg \Leftarrow)$$

The double line in the above represents that applications of $\wedge \Rightarrow$-rule and contraction-rule are omitted.

IV. Concluding remarks

We proposed the tense-interval logic which combined linear tense logic and interval logic. In our logic, temporal relations between intervals are reduced to the accessibility of possible worlds, given inclusion relations. We showed that our logic provided a formal apparatus for a precise aspectual classification. Lastly, we introduced a sequent system for our logic and showed its decidability.

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