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A general theory of tempo-logical connectives in Mental Image Description Language L_{md}

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Abstract: The knowledge representation language L_{md} has been proposed in the Mental Image Directed Semantic Theory (MIDST) in order to facilitate intuitive human-system interaction in the real world. The L_{md} has employed the 'tempo-logical connectives (TLCs)' to represent both temporal and logical relations between two events, and the 'temporal conjunctions', a subset of TLCs, have already been applied to formulating natural event concepts, namely, those represented in natural language. This paper presents the theory of TLCs extended for formalizing natural spatiotemporal knowledge in general in order to facilitate intuitive human-system interaction such as comprehensible communication in natural language between ordinary people and home robots.

Keywords: Temporal logic, Knowledge representation language.

I. INTRODUCTION

There have been several theories about formalization and computation of spatial or temporal relations and a considerable number of their applications [1-6]. They, however, do not necessarily keep tight correspondence with spatiotemporal expressions in natural language reflecting human cognitive processes strongly [7, 8]. For example, consider such expressions as S1 and S1′.

(S1) It got cloudy ***and*** it rained.

(S1′) It rained ***and*** it got cloudy.

It is very natural for people to understand each one by synthesizing the mental images evoked by the two clauses into an intuitively plausible one where spatiotemporal relations of the matters involved do not conflict with their empirical knowledge of the real world. In this case, people would make a special effort to arrange the two events, namely, 'getting cloudy' and 'raining' on the time axis adequately because the temporal relation between them is not explicit in either expression. According to the results of our psycholinguistic experiments [6], people are apt to interpret the construction 'A happened ***and*** B happened' in spatiotemporal expressions as a specific event, namely, as 'A happened ***before*** B happened' (c.f., S3′). That is, people usually do not understand such expressions as S1 and S1′ in the same meaning as '$A \wedge B$' equivalent to '$B \wedge A$' in pure logic.

Consider another expression S2 below.

(S2) It gets cloudy ***before*** it rains.

People usually interpret the construction '*A* happens *before B* happens' as a general causality, namely, as 'If *B* happens, *A* happens in advance.' This is easily understood by the fact that S2 and S2′ are not semantically identical while S3 and S3′ can refer to the same compound event as S1. That is, it is not always the case that cloudiness is followed by rain.

(S2′) It rains ***after*** it gets cloudy.

(S3) It got cloudy ***before*** it rained.

(S3′) It rained ***after*** it got cloudy.

The point-based time theories can formalize the constructions of S1 and S2 as (1) and (2), respectively, where the events *A* and *B* are unnaturally but inevitably to be provided with the time points and their relations. Here and after, a time point 't_i' is represented as a real number (i.e., $t_i \in \boldsymbol{R}$).

$$(\exists t_1,t_2)A(t_1)\wedge B(t_2)\wedge t_1<t_2 \quad (1)$$

$$(\exists t_1)(\forall t_2)(B(t_2) \supset A(t_1))\wedge t_1<t_2 \quad (2)$$

On the other hand, the interval-based time theories can provide a counterpart for (1) as (3), possibly more naturally, but not for (2) because such a predicate as *'after'*, *'contains'* or so is intrinsically a conjunction (i.e., '$\wedge$') furnished with a certain ***purely*** temporal relation. That is, (3) could be formalized otherwise as (4), where *A* and *B* are parameterized with time-intervals $[t_{11},t_{12}]$ and $[t_{21},t_{22}]$, respectively, presuming that $t_{11}<t_{12}$ and $t_{21}<t_{22}$.

$$before(A,B)(\equiv after(B,A)) \quad (3)$$

$$(\exists t_{11},t_{12},t_{21},t_{22})A([t_{11},t_{12}])\wedge B([t_{21},t_{22}])\wedge t_{12}<t_{21} \quad (4)$$

The Mental Image Directed Semantic Theory (MIDST) is intended to provide a formal system for natural semantics and general knowledge of space and time [7]. This formal system is one kind of applied predicate logic consisting of definitions and postulates subject to human perceptive processes of space and time while other similar systems [e.g., 1-5] in Artificial Intelligence are objective, namely, independent of human perception and do not necessarily keep tight correspondences with natural language.

The MIDST has proposed a systematic method to model natural event concepts as 'loci in attribute spaces', so called, and describe them in a formal language L_{md}, where a general locus is to be articulated by "Atomic

Locus" over a certain time-interval formulated as (5) so called "Atomic locus formula".

$$L(x,y,p,q,a,g,k) \quad (5)$$

The intuitive interpretation of (1) is given as follows. ***"Matter 'x' causes Attribute 'a' of Matter 'y' to keep (p=q) or change (p ≠ q) its values temporally (g=Gt) or spatially (g=Gs) over a time-interval, where the values 'p' and 'q' are relative to the standard 'k'."***

L_{md} is employed for many-sorted predicate logic provided with 'tempo-logical connectives (TLCs)' with which to represent both temporal and logical relations between two loci over certain time-intervals. Therefore, TLCs are for interval-based time theories but are generalized for all the binary logical connectives (i.e., conjunction '∧', disjunction '∨', implication '⊃' and equivalence '≡') unlike the conventional ones exclusively for the conjunction [1]. This is intended for facilitating formulation and computation of people's empirical (i.e., natural) knowledge pieces such as S1 and S2 that are possibly formalized as (1)-(4) in the conventional schemes. This paper presents a brief sketch of L_{md}, a general theory of TLCs and its application to formulating human empirical knowledge expressed in spatiotemporal language.

II. TEMPOLOGICAL CONNECTIVES

The definition of a tempo-logical connective K_i is given by **D1**, where τ_i, χ and K refer to one of ***purely*** temporal relations indexed by an integer 'i', a locus, and an ordinary binary logical connective such as the conjunction '∧', respectively.

The definition of each τ_i is provided with Table 1 implying the theorem **T1**, where the durations of χ_1 and χ_2 are $[t_{11}, t_{12}]$ and $[t_{21}, t_{22}]$, respectively. This table shows the complete list of temporal relations between two intervals, where 13 types of relations are discriminated by the suffix 'i' ($-6 \leq i \leq 6$). This is in accordance with the conventional notation [1] which, to be strict, is for 'temporal conjunctions ($=\wedge_i$)' but not for pure 'temporal relations ($=\tau_i$)'.

D1. $\chi_1 K_i \chi_2 \Leftrightarrow (\chi_1 K \chi_2) \wedge \tau_i(\chi_1, \chi_2)$

T1. $\tau_{-i}(\chi_2, \chi_1) \equiv \tau_i(\chi_1, \chi_2) \quad (\forall i \in \{0,\pm1,\pm2,\pm3,\pm4,\pm5,\pm6\})$

(Proof) Trivial in Table1. **[Q.E.D.]**

As easily understood, the properties of a TLC depend on those of the purely logical connective (K) and the temporal relations (τ_i) involved. By the way, there are a considerable number of trivial theorems concerning temporal relations such as (6)-(13) below.

$$(\forall i)\tau_i(\chi_1,\chi_2) \wedge \tau_0(\chi_2,\chi_3) .\supset. \tau_i(\chi_1,\chi_3) \quad (6)$$
$$\tau_1(\chi_1,\chi_2) \wedge \tau_1(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (7)$$
$$\tau_1(\chi_1,\chi_2) \wedge \tau_3(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (8)$$
$$\tau_1(\chi_1,\chi_2) \wedge \tau_4(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (9)$$
$$\tau_1(\chi_1,\chi_2) \wedge \tau_5(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (10)$$
$$\tau_1(\chi_1,\chi_2) \wedge \tau_6(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (11)$$
$$\tau_2(\chi_1,\chi_2) \wedge \tau_1(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (12)$$
$$\tau_5(\chi_1,\chi_2) \wedge \tau_1(\chi_2,\chi_3) .\supset. \tau_5(\chi_1,\chi_3) \quad (13)$$

In order explicit indication of ***absolute*** time elapsing, 'Empty Event' denoted by 'ε' is introduced as **D2** with the attribute 'Time Point (A_{34})' and the Standard of absolute time 'T_a'. Usually people can know only a certain ***relative*** time point by a clock that is seldom exact and that is to be denoted by another Standard in the L_{md}. Hereafter, Δ denotes the total set of absolute time intervals. According to this scheme, the suppressed absolute time-interval $[t_a, t_b]$ of a locus χ can be indicated as (14).

D2. $\varepsilon([t_i,t_j]) \Leftrightarrow (\exists x,y,g)L(x,y,t_i,t_j,A_{34},g,T_a)$,
where $[t_i, t_j] \in \Delta$ $(=\{[t_1, t_2] \mid t_1 < t_2 \ (t_1, t_2 \in \mathbf{R})\})$. □

$$\chi \Pi \varepsilon([t_a,t_b]) \quad (14)$$

A locus corresponding directly to the live image of a specific phenomenon outside is called 'Perceptual Locus' and can be formulated with atomic locus formulas and temporal conjunctions such as SAND ($\wedge_0$ or Π) and CAND ($\wedge_1$ or •). This is not necessarily the case for the other type of locus, so called, 'Conceptual Locus' that does not correspond directly to such a live image but to such a generalized mental image or knowledge piece as is conventionally represented by (2) with logical connectives other than conjunctions also involved. This is essentially due to no interpreting a negated atomic locus formula as a locus with ***a unique time-interval***. That is, **D1** is exclusively for perceptual loci so far as it is.

Whereas, such theses as '$A \vee B .\equiv. \sim(\sim A \wedge \sim B)$' and '$A \supset B .\equiv. \sim A \vee B$' in pure logic can give us a good reason for the identity of a locus formula with its negative in absolute time-interval, that is, negation-freeness of absolute time passing under a locus referred to by its suppressed absolute time-interval. Therefore, in order to make **D1** valid also for conceptual loci, we introduce a meta-function δ defined by **D3** and its related axioms **A1** and **A2** as follows, where δ is to extract the ***suppressed*** absolute interval of a locus formula χ.

Table 1. List of temporal relations[†]

Definition of τ_i		Allen's notation
$t_{11}=t_{21} \wedge t_{12}=t_{22}$	$\tau_0(\chi_1, \chi_2)$	equals(χ_1,χ_2)
	$\tau_0(\chi_2, \chi_1)$	equals(χ_2, χ_1)
$t_{12}=t_{21}$	$\tau_1(\chi_1, \chi_2)$	meets(χ_1, χ_2)
	$\tau_{-1}(\chi_2, \chi_1)$	met-by(χ_2, χ_1)
$t_{11}=t_{21} \wedge t_{12}<t_{22}$	$\tau_2(\chi_1, \chi_2)$	starts(χ_1, χ_2)
	$\tau_{-2}(\chi_2, \chi_1)$	started-by(χ_2, χ_1)
$t_{11}>t_{21} \wedge t_{12}<t_{22}$	$\tau_3(\chi_1, \chi_2)$	during(χ_1, χ_2)
	$\tau_{-3}(\chi_2, \chi_1)$	contains(χ_2, χ_1)
$t_{11}>t_{21} \wedge t_{12}=t_{22}$	$\tau_4(\chi_1, \chi_2)$	finishes(χ_1, χ_2)
	$\tau_{-4}(\chi_2, \chi_1)$	finished-by(χ_2, χ_1)
$t_{12}<t_{21}$	$\tau_5(\chi_1, \chi_2)$	before(χ_1, χ_2)
	$\tau_{-5}(\chi_2, \chi_1)$	after(χ_2, χ_1)
$t_{11}<t_{21} \wedge t_{21}<t_{12} \wedge t_{12}<t_{22}$	$\tau_6(\chi_1, \chi_2)$	overlaps(χ_1, χ_2)
	$\tau_{-6}(\chi_2, \chi_1)$	overlapped-by(χ_2, χ_1)

[†]The durations of χ_1 and χ_2 are $[t_{11}, t_{12}]$ and $[t_{21}, t_{22}]$, respectively.

D3. $\delta(\chi)\in\Delta$

A1. $\delta(\sim\alpha)=\delta(\alpha)$,

where α is an atomic locus formula.

A2. $\delta(\chi)=[t_{min}, t_{max}]$,

where t_{min} and t_{max} are respectively the minimum and the maximum time-point included in the absolute time-intervals of the atomic locus formulas, either positive or negative, within χ.

These axioms lead to **T2** (Theorem of negation-freeness of a suppressed absolute time-interval) below.

T2. $\delta(\sim\chi)=\delta(\chi)$

(Proof) According to **A1** and **A2**, the time-interval of each atomic locus formula involved in $\sim\chi$ is negation-free and therefore so are t_{min} and t_{max} in $\delta(\sim\chi)$. **[Q.E.D.]**

The counterpart of the contraposition in pure logic (i.e., $A\supset B.\equiv.\sim B\supset\sim A$) is given as **T3** (Tempo-logical Contraposition) whose rough proof is as follows immediately below, where the left hand of ':' refers to the theses (e.g., **PL** is a subset of those in pure predicate logic) employed at the process indicated by the conventional meta-symbol '$\rightarrow$' or '$\leftrightarrow$' for deduction.

T3. $\chi_1\supset_i\chi_2.\equiv.\sim\chi_2\supset_{-i}\sim\chi_1$

(Proof)

D1: $\chi_1\supset_i\chi_2 \leftrightarrow (\chi_1\supset\chi_2)\wedge\tau_i(\chi_1,\chi_2)$

PL: $\leftrightarrow (\sim\chi_2\supset\sim\chi_1)\wedge\tau_i(\chi_1,\chi_2)$

T2: $\leftrightarrow (\sim\chi_2\supset\sim\chi_1)\wedge\tau_i(\sim\chi_1,\sim\chi_2)$

D1: $\leftrightarrow (\sim\chi_2\supset\sim\chi_1)\wedge\tau_{-i}(\sim\chi_2,\sim\chi_1)$

D1: $\leftrightarrow \sim\chi_2 \supset_{-i} \sim\chi_1$ **[Q.E.D.]**

III. APPLICATION OF TLCs

Perceptual loci are inevitably articulated by tempological conjunctions. For example, (3) or (4) is represented as (15).

$$A\wedge_5 B\ (\equiv B\wedge_{-5}A) \quad (15)$$

As easily understood, any pair of loci temporally related in certain attribute spaces can be formulated as (16)-(20) in exclusive use of SANDs, CANDs and empty events.

$$\chi_1 \wedge_2 \chi_2 .\equiv. (\chi_1\bullet\varepsilon)\Pi\chi_2 \quad (16)$$

$$\chi_1 \wedge_3 \chi_2 .\equiv. (\varepsilon_1\bullet\chi_1\bullet\varepsilon_2)\Pi\chi_2 \quad (17)$$

$$\chi_1 \wedge_4 \chi_2 .\equiv. (\varepsilon\bullet\chi_1)\Pi\chi_2 \quad (18)$$

$$\chi_1 \wedge_5 \chi_2 .\equiv. \chi_1\bullet\varepsilon\bullet\chi_2 \quad (19)$$

$$\chi_1 \wedge_6 \chi_2 .\equiv. (\chi_1\bullet\varepsilon_3)\Pi(\varepsilon_1\bullet\chi_2)\Pi(\varepsilon_1\bullet\varepsilon_2\bullet\varepsilon_3) \quad (20)$$

Consider such somewhat complicated sentences as S10 and S11. The underlined parts are deemed to refer to some events neglected in time and in space, respectively. These events correspond with skipping of FAOs and are called 'Temporal Empty Event' and 'Spatial Empty Event', denoted by 'ε_t' and 'ε_s' as empty events with $g=G_t$ and $g=G_s$ at **D2**, respectively. The concepts of S4 and S5 are given by (21) and (22), where 'A_{15}' and 'A_{17}' represent the attribute 'Trajectory' and 'Mileage', respectively.

(S4) The *bus* runs 10km straight east from A to B, and *after a while*, at C it meets the street with the sidewalk.

$$(\exists x_1,x,y,z,p,q,k,k_1,k_2,k_3)\ (L(x_1,x,A,B,A_{12},G_t,k)\ \Pi\ L(x_1,x,0,10km,A_{17},G_t,k_1)\Pi\ L(x_1,x,Point,Line,A_{15},G_t,k_2)\ \Pi L(x_1,x,East,East,A_{13},G_t,k_3))\bullet\ \varepsilon_t\bullet L(x_1,x,p,C,A_{12},G_t,k)\ \Pi\ L(x_1,y,q,C,A_{12},G_s,k)\Pi\ L(x_1,z,y,y,A_{12},G_s,k))\ \wedge bus(x)\wedge street(y)\wedge sidewalk(z)\wedge p\neq q \quad (21)$$

(S5) The *road* runs 10km straight east from *A* to *B*, and *after a while*, at *C* it meets the street with the sidewalk.

$$(\exists x_1,x,y,z,p,q,k,k_1,k_2)(L(x_1,x,A,B,A_{12},G_s,k)\Pi\ L(x_1,x,0,10km,A_{17},G_s,k_1)\Pi L(x_1,x,Point,Line,A_{15},G_s,k_2)\ \Pi L(x_1,x,East,East,A_{13},G_s,k_3))\bullet\varepsilon_s\bullet L(x_1,x,p,C,A_{12},G_s,k)\ \Pi\ L(x_1,y,q,C,A_{12},G_s,k)\Pi L(x_1,z,y,y,A_{12},G_s,k))\ \wedge road(x)\wedge street(y)\wedge sidewalk(z)\wedge p\neq q \quad (22)$$

From the viewpoint of cross-media reference, the formula (22) can refer to such a spatial event depicted as the still picture in Fig.11 while (21) can be interpreted into a motion picture.

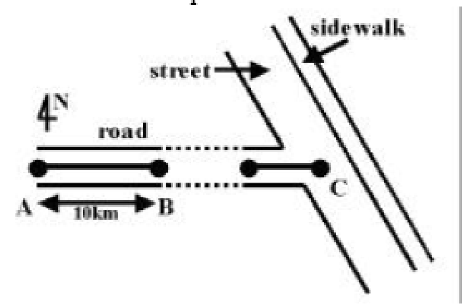

Fig.11. Pictorial interpretation of the formula (22).

On the other hand, the causality represented by (2) can be formulated as (23) by employing the temporal implication '$\supset_5$' or as its equivalent (24) with '$\supset_{-5}$'. As easily understood, these formulas are equivalent to such ones using temporal disjunctions as parenthesized. By the way, (24) can be verbalized as S6.

$$B.\supset_{-5}.A \quad (\equiv\sim B\vee_{-5}A) \quad (23)$$

$$\sim A.\supset_5.\sim B\ (\equiv A\vee_5 \sim B) \quad (24)$$

(S6) Unless it gets cloudy, it does not rain later.

Tempological conjunctions are also applied to formulating event patterns involved in such verb concepts as 'carry', 'return' and 'fetch' [11] and temporal implications are often employed for formalizing miscellaneous tempo-logical relations between event concepts as knowledge pieces without explicit indication of time-intervals. For example, an event 'fetch(x,y)' is necessarily *finished by* an event 'carry(x,y)' [11]. This fact can be formulated as (25), which is not an axiom but a theorem deducible from the definitions of event concepts here. Similarly, the tempo-logical relation between 'fetch(x,y)' and 'return(x)' can be theorematized as (26). Furthermore, if necessary, these can be temporally quantified as (27) and (28), respectively, where $d_1, d_2 \in\Delta$.

$$(\forall x,y)fetch(x,y).\supset_{-4}.carry(x,y) \quad (25)$$

$$(\forall x,y)fetch(x,y)\supset_0 return(x) \quad (26)$$

$$(\exists d_2)(\forall d_1)(\forall x,y)fetch(x,y)\Pi\delta(d_1).\supset_{-4}.carry(x,y)\Pi\delta(d_2) \quad (27)$$

$$(\exists d_2)(\forall d_1)(\forall x,y)fetch(x,y)\Pi\delta(d_1).\supset_0.return(x)\Pi\delta(d_2) \quad (28)$$

The postulate PRS [11] can be formulated as **P1** using '$\equiv_0$', where χ and χ^R is a perceptual locus and its 'reversal' for a certain spatial event, respectively. These loci are substitutable with each other due to the property of '$\equiv_0$'.

P1. $\chi^R .\equiv_0 \chi$

The recursive operations to transform χ into χ^R are defined by **D4**, where the reversed values p^R and q^R depend on the properties of the attribute values p and q. For example, at (22), $p^R=p$, $q^R=q$ for A_{12}; $p^R=-p$, $q^R=-q$ for A_{13}.

D4. $(\chi_1 \bullet \chi_2)^R \Leftrightarrow \chi_2^R \bullet \chi_1^R$
$(\chi_1 \Pi \chi_2)^R \Leftrightarrow \chi_1^R \Pi \chi_2^R$
$(L(x,y,p,q,a,G_s,k))^R \Leftrightarrow L(x,y,q^R,p^R,a,G_s,k)$

According to **D4**, (22) is transformed into (29) as its reversal and equivalent in PRS to be verbalized as S13.

$$(\exists x_1,x,y,z,p,q,k,k_1,k_2,k_3)(L(x_1,x,C,p,A_{12},G_s,k)\Pi L(x_1,y,C,q,A_{12},G_s,k)\Pi L(x_1,z,y,y,A_{12},G_s,k)) \bullet \varepsilon_s \bullet (L(x_1,x,B,A,A_{12},G_s,k)\Pi L(x_1,x,0,10km,A_{17},G_s,k_1) \Pi L(x_1,x,Point,Line,A_{15},G_s,k_2) \Pi L(x_1,x,West,West,A_{13},G_s,k_3)) \wedge road(x)\wedge street(y)\wedge sidewalk(z)\wedge p\neq q \quad (29)$$

(S7) The road separates at *C* from the street with the sidewalk and, after a while, runs 10km straight west from *B* to *A*.

IV. TEMPOLOGICAL DEDUCTION

The proof of such a formula as (30) is given by a set of deductions formulated as (31).

$$P \supset_n Q \quad (30)$$

$$X \rightarrow_{i(j)} Y, \quad (31)$$

where $\tau_i(X,Y)$ and $\tau_j(P,Y)$, and j=n when Y=Q.

For example, consider the propositions A-F below and we can understand F can be deduced from D and E.

A='Tom studies'
B='Tom is scolded'
C='Tom is given candies'
D='Tom does not study unless he is scolded in advance'
E='Tom studies immediately before he is given candies'
F= 'Tom is not given candies unless he is scolded in advance'

, where D, E and F are formulated as (32)-(34), respectively.

$$D \;\equiv.\; \sim B \supset_5 \sim A \quad (32)$$

$$E \;\equiv.\; C \supset_{-1} A \quad (33)$$

$$F \;\equiv.\; \sim B \supset_5 \sim C \quad (34)$$

The proof is as follows.

(Proof)
E, T3: $\sim A \supset_1 \sim C$ (C1)
D: $\sim B \rightarrow_{5(5)} \sim A$
C1: $\rightarrow_{1(5)} \sim C$

$\therefore \sim B \supset_5 \sim C$
[Q.E.D]

V. CONCLUSION

In order to realize more intuitive human-system interaction, the author extended the theory of tempo-logical connectives so as to be applicable to general natural spatiotemporal knowledge. This extension was concentrated on providing the theory with tempo-logical connectives other than tempo-logical conjunctions, where the principal definitions and postulates have been induced from several psycholinguistic experiments [7]. To remark reversely, the theses deduced from them have been already psycholinguistically validated. The MIDST is intended to provide a formal system represented in L_{md} for natural or intuitive semantics of spatiotemporal language [8]. This formal system is one kind of applied predicate logic consisting of axioms and postulates subject to human perception of space and time while the other similar systems in Artificial Intelligence [1-5] are objective, namely, independent of human perception and do not necessarily keep tight correspondences with natural language.

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