Systematic Formulation and Computation of Subjective Spatiotemporal Knowledge Based on Mental Image Directed Semantic Theory: Toward a Formal System for Natural Intelligence

Masao Yokota

Department of System Management, Faculty of Information Engineering
Fukuoka Institute of Technology
3-30-1, Wajiro-higashi, Higashi-ku, Fukuoka-shi, 811-0295, Japan

Abstract. The author has been challenging to model natural intelligence as a formal system based on his original semantic theory "Mental Image Directed Semantic Theory (MIDST)". As the first step for this purpose, this paper presents a brief sketch of the attempt on systematic representation and computation of subjective spatiotemporal knowledge in natural language based on certain hypotheses of mental image in human.

1 Introduction

The author and his co-workers have been studying integrated multimedia understanding for intuitive human-robot interaction, that is, interaction between non-expert or ordinary people and home robots [1, 2]. In such a situation, natural language is the leading information medium for their communication as well as for the communication between ordinary people because it can convey the exact intention of the sender to the receiver due to its syntax and semantics common to its users, which is not necessarily the case for another medium such as gesture or so. For such an intuitive human-robot interaction intended here, it is essential to develop a systematically computable knowledge representation language (KRL) as well as representation-free technologies such as neural networks for processing unstructured sensory/motory data. This type of language is indispensable to knowledge-based processing such as understanding sensory events, planning appropriate actions and knowledgeable communication with ordinary people in natural language, and therefore it needs to have at least a good capability of representing spatiotemporal events that correspond to human/robotic sensations and actions in the real world. Most of conventional methods have provided robotic systems with such quasi-natural language expressions as 'move(Velocity, Distance, Direction)', 'find(Object, Shape, Color)' and so on for human instruction or suggestion, uniquely related to computer programs to deploy sensors/ motors [3, 4]. These expression schemas, however, cannot provide a firm bridge between natural language and programs [5], and what is worse is that they are

Yokota M. (2009).
Systematic Formulation and Computation of Subjective Spatiotemporal Knowledge Based on Mental Image Directed Semantic Theory: Toward a Formal System for Natural Intelligence.
In *Proceedings of the 6th International Workshop on Natural Language Processing and Cognitive Science* , pages 133-142
DOI: 10.5220/0002203701330142

too linguistic or coarse to represent and compute sensory/motory events in such an integrated way as intended here.

In order to solve this problem, the author has employed the formal language so called 'Language for Mental-image Description ($\boldsymbol{L_{md}}$)' proposed in his original semantic theory 'Mental Image Directed Semantic Theory (MIDST)' [1, 2]. The key idea of MIDST is the model of human attention-guided (i.e. active) perception yielding omnisensory images that inevitably reflect certain movements of the focus of attention of the observer (FAO) scanning certain matters in the world, either inside or outside of the mind. More analytically, these omnisensory images are associated with spatiotemporal changes (or constancies) in certain attributes of the matters scanned by FAO and modeled as temporally parameterized "loci in attribute spaces", so called, to be formulated in the formal language $\boldsymbol{L_{md}}$. This language has already been implemented on several types of computerized intelligent systems including IMAGES-M [1, 2]. The most remarkable feature of $\boldsymbol{L_{md}}$ is its capability of formalizing spatiotemporal matter concepts grounded in human/robotic sensation while the other similar KRLs are designed to describe the logical relations among conceptual primitives represented by lexical tokens [6, 7] with the risk of "predicate drift" [8]. The final goal of this study is to build a formal system for natural intelligence so as to facilitate intuitive but ***coherent*** interaction between ordinary people and robots. A formal system is defined as a pair of a formal language and a deductive system consisting of the axioms and inference rules employed for theorem derivation. $\boldsymbol{L_{md}}$ is a formal language for many-sorted predicate logic with 5 types of terms specific to the mental image model. Therefore, the deductive system intended here is to be based on the deductive apparatus for predicate logic.

The remainder of this paper is organized as follows. Section 2 introduces the formal system intended here, presenting a number of postulates of human subjective knowledge pieces about space and time. Conclusions and planned future work are given in the final section.

2 Formal System for Natural Intelligence

The symbols of $\boldsymbol{L_{md}}$ for the deductive system are listed as (i)-(ix) below. These symbols are possibly subscripted just like A_{01}, G_s, etc.

(i) logical connectives: $\sim, \wedge, \vee, \supset, \equiv$
(ii) quantifiers : $\forall, \exists$
(iii) auxiliary constants : ., (,)
(iv) sentence variables : χ
(v) predicate variables : ψ
(vi) individual variables
  a) matter variables : x, y, z
  b) attribute variables : a
  c) value variables : p, q, r, s, t
  d) pattern variables : g
  e) standard variables : k
(vii) sentence constants : N

(viii) predicate constants : L, =, ≠, >, < (and others to be introduced where needed)
(ix) individual constants
a) matter constants : to be introduced where needed
b) attribute constants : A, B
c) value constants : to be introduced where needed
d) pattern constants : G
e) standard constants : K
(x) function constants: arithmetic operators such as +, -, etc. (and others to be introduced where needed)
(xi) meta-symbols: ⇔, →, ↔ (and others to be introduced where needed)
(xii) others: to be defined by the symbols above.

The system is a many-sorted predicate logic with five kinds of individuals employed for one special predicate constant '*L*' so called 'Atomic Locus'. Except this point, the syntactic rules and the theses of the system are the same as those of the conventional predicate logic. The predicate '*L*' is such a seven-place predicate as is given by expression (1).

$$L(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6, \omega_7) \quad (1)$$

Expression (1) is a well-formed formula (i.e. wff) called 'Atomic locus formula' if and only if the conditions below are satisfied. A well-formed formula consisting of atomic formulas and logical connectives is called simply 'Locus formula'.

(a) ω_1 is a matter term (variable or constant)
(b) ω_2 is a matter term
(c) ω_3 is a value or a matter term
(d) ω_4 is a value or a matter term
(e) ω_5 is an attribute term
(f) ω_6 is a pattern term
(g) ω_7 is a standard (or matter) term

The intuitive interpretation of (1) is given as follows.

"Matter ω_1 causes Attribute ω_5 of Matter ω_2 to keep ($\omega_3 = \omega_4$) or change ($\omega_3 \neq \omega_4$) its values temporally (ω_6 =Gt) or spatially (ω_6 =Gs) over a certain absolute time-interval, where the values ω_3 and ω_4 are relative to the standard ω_7."

Here, Matter terms at Values or Standard represent their values in each place at the time or over the time-interval. When $\omega_6=G_t$, the locus indicates monotonic change (or constancy) of the attribute in time domain, and when $\omega_6=G_s$, that in space domain. The former is called 'temporal event' and the latter, 'spatial event'. For example, the motion of the 'bus' represented by S1 is a temporal event and the ranging or extension of the 'road' by S2 is a spatial event whose meanings or concepts are formulated as (2) and (3), respectively, where 'A_{12}' denotes the attribute 'Physical Location'. These two formulas are different only at the term 'Pattern'.

(S1) The bus runs from Tokyo to Osaka.
(S2) The road runs from Tokyo to Osaka.

$$(\exists x,y,k)L(x,y,Tokyo,Osaka,A_{12},G_t,k)\wedge bus(y) \quad (2)$$

$$(\exists x,y,k)L(x,y,Tokyo,Osaka,A_{12},G_s,k)\wedge road(y) \quad (3)$$

It has been often argued that human active sensing processes may affect perception and in turn conceptualization and recognition of the physical world while such cognitive processes or products have seldom been formulated for computation [9-12]. The author has hypothesized that the difference between temporal and spatial event concepts can be attributed to the relationship between the Attribute Carrier (AC) (i.e. the matters at ω_2) and the Focus of the Attention of the Observer (FAO). To be brief, it is hypothesized that FAO is fixed on the whole AC in a temporal event but *runs* about on the AC in a spatial event. Consequently, the *bus* and FAO move together in the case of S1 while FAO solely moves along the *road* in the case of S2. That is, ***all loci in attribute spaces are assumed to correspond one to one with movements or, more generally, temporal events of FAO***. The duration of a locus corresponds to an absolute time-interval over which FAO is put on the corresponding phenomenon outside or inside the mind. Such an absolute time-interval is suppressed in an atomic locus formula because it is assumed that people cannot measure the absolute time by any chronograph but a certain relative time (Actually, people do not always consult a chronograph even if they can). MIDST has employed 'tempo-logical connectives (TLCs)', to be introduced later, denoting both logical and temporal relations between loci by themselves because these must be considered simultaneously in locus articulation. The attribute spaces for humans correspond to the sensory receptive fields in their brains. At present, about 50 attributes (i.e. Attribute Constants) have been extracted exclusively from Japanese and English words [13]. Correspondingly, 6 categories of standards (i.e. Standard Constants) [1, 2] have been extracted after the conventional categorization [9] assumed necessary for representing values of each attribute. In general, the attribute values represented by words are relative to certain standards. These standards are to be utilized exclusively for coping with vagueness and controlling granularity of attribute values.

The deductive system employs '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 with relative temporal relations but are generalized for all the binary logical connectives (i.e. conjunction '$\wedge$', disjunction '$\vee$', implication '$\supset$' and equivalence '$\equiv$') unlike the conventional ones exclusively for the conjunction [14, 15]. The definition of a tempo-logical connective C_i is given by **D1**, where τ_i, χ and C refer to one of ***pure*** temporal relations indexed by an integer '*i*', a locus, and an ordinary binary logical connective such as the conjunction '$\wedge$', respectively. The definition of each τ_i discriminates 13 types of temporal relations by the integer suffix '*i*' ranging from –6 to 6, respectively corresponding to 'overlapped-by', 'after', 'finished-by', 'contains', 'started-by', 'met-by', 'equals', 'meets', 'starts', 'during', 'finishes' 'before', and 'overlaps'. This is in accordance with the conventional notation [15] which, to be strict, is for 'temporal conjunctions ($=\wedge_i$)' but not for pure 'temporal relations ($=\tau_i$)'. The TLCs used most frequently are 'SAND ($\wedge_0$)' and 'CAND ($\wedge_1$)', standing for 'Simultaneous AND' and 'Consecutive AND' and conventionally symbolized as 'Π' and '•', respectively.

D1. $\chi_1 \; C_i \; \chi_2 \Leftrightarrow (\chi_1 \; C \; \chi_2) \wedge \tau_i(\chi_1, \chi_2)$
where $\tau_{-i}(\chi_2, \chi_1) \equiv \tau_i(\chi_1, \chi_2)$ $(\forall i \in \{0,\pm1,\pm2,\pm3,\pm4,\pm5, \pm6\})$

In order for 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 'K_{Ta}', where ***R*** and ***Δ*** denote the total sets of real numbers and absolute time intervals, respectively. (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 $\boldsymbol{L_{md}}$.) According to this scheme, the suppressed absolute time-interval $[t_a, t_b]$ of a locus χ can be indicated as (4).

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

$$\chi \Pi \varepsilon([t_a,t_b]) \tag{4}$$

People can transform their mental images in several ways such as mental rotation [16]. Here are introduced and defined two kinds of such mental operations, namely, 'reversal' and 'duplication'. For example, people can easily imagine the reversal of an event just like 'rise' versus 'sink'. This mental operation is here denoted as 'R' and recursively defined as **D3**, where χ_i stands for a locus. The reversed values p^R and q^R depend on the properties of the attribute values p and q. For example, p^R =p, q^R =q for A_{12}; p^R =-p, q^R =-q for A_{13}.

D3. $(\chi_1 \bullet \chi_2)^R \Leftrightarrow \chi_2^R \bullet \chi_1^R$
$(\chi_1 \Pi \chi_2)^R \Leftrightarrow \chi_1^R \; \Pi \chi_2^R$
$L^R(x,y,p,q,a,g,k) \Leftrightarrow L(x,y,q^R,p^R,a,g,k)$

For another example, people can easily imagine the duplication or repetition of an event just like 'visit twice' versus 'visit once'. This operation is also recursively defined as **D4**, where 'n' is an integer representing the frequency of a locus formula χ.

D4. $\chi^n \Leftrightarrow \chi$ (n=1)
$\chi^n \Leftrightarrow \chi \bullet \chi^{n-1}$ (n>1)

An event here, usually referred by a verb, preposition, adjective or so in natural language, is defined as a spatiotemporal relation among certain matters in the world, which is to be conceptualized as a generalization of a perceptual locus, namely, a combination of atomic loci articulated by tempological conjunctions (i.e. $\wedge_i$) with the abstraction operator 'λ'. For example, the English verb concepts 'carry (=convey)' and 'shuttle' are to be defined as (5) and (6), respectively. These can be depicted as Fig.1-a and b, respectively. In turn, the expression (7) is the definition of the English verb concept 'fetch' depicted as Fig.1-c. This implies such a temporal event that 'x' goes for 'y' and then comes back with it. In the same way, the English verb concept 'hand' or 'receive' depicted as Fig.1-d is defined equivalently as (8) or its abbreviation (9) where Event Causers (i.e. the matters at ω_1) are merged into a set. Such locus formulas as correspond with natural event concepts are called 'Event Patterns' and about 40 kinds have been found concerning the attribute 'Physical Location (A_{12})' [1,2].

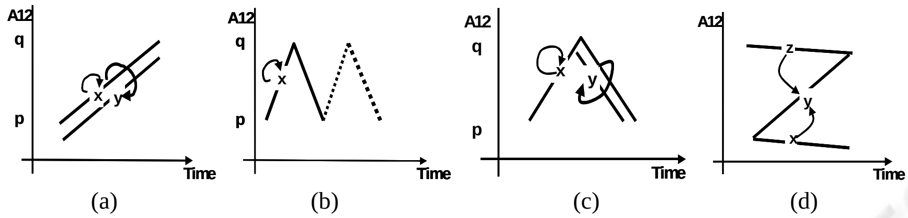

Fig.1. Pictorial interpretation of (a) 'carry', (b) 'shuttle', (c) 'fetch' and (d) 'hand/receive'.

$$(\lambda x,y)\mathrm{carry}(x,y)\Leftrightarrow(\lambda x,y)\mathrm{convey}(x,y)\Leftrightarrow(\lambda x,y)(\exists p,q,k)L(x,x,p,q,A_{12},G_t,k)\Pi L(x,y,p,q,A_{12},G_t,k)\wedge x\neq y\wedge p\neq q \quad (5)$$

$$(\lambda x)\mathrm{shuttle}(x)\Leftrightarrow(\lambda x)(\exists p,q,k)(L(x,x,p,q,A_{12},G_t,k)\bullet L^R(x,x,p,q,A_{12},G_t,k))^n\wedge p\neq q \wedge n\geq 1\Leftrightarrow(\lambda x)(\exists p,q,k)(L(x,x,p,q,A_{12},G_t,k)\bullet L(x,x,q,p,A_{12},G_t,k))^n\wedge p\neq q\wedge n\geq 1 \quad (6)$$

$$(\lambda x,y)\mathrm{fetch}(x,y)\Leftrightarrow(\lambda x,y)(\exists p_1,p_2,k)L(x,x,p_1,p_2, A_{12},G_t,k) \bullet((\underline{L(x,x,p_2,p_1,A_{12},G_t,k)\ \Pi L(x,y,p_2,p_1, A_{12},G_t,k)})\wedge x\neq y\wedge p_1\neq p_2 \quad (7)$$

$$(\lambda x,y,z)\mathrm{hand}(x,y,z)\Leftrightarrow(\lambda x,y,z)\mathrm{receive}(z,y,x) \Leftrightarrow(\lambda x,y,z)(\exists k)L(x,y,x,z,A_{12},G_t,k)\Pi L(z,y,x,z,A_{12},G_t,k)\wedge x\neq y\wedge y\neq z\wedge z\neq x \quad (8)$$

$$\Leftrightarrow(\lambda x,y,z)(\exists k)L(\{x,z\},y,x,z,A_{12},G_t,k)\wedge x\neq y\wedge y\neq z\wedge z\neq x \quad (9)$$

Employing TLCs, tempo-logical relationships between miscellaneous event concepts can be formulated without explicit indication of time intervals. For example, an event 'fetch(x,y)' is necessarily *finished by* an event 'carry(x,y)' as indicated by the underline at (7). This fact can be formulated as (10), where '$\supset_{-4}$' is the '*implication* ($\supset$)' furnished with the temporal relation '*finished-by* (τ_{-4})'. This kind of formula is not an axiom but a theorem deducible from the definitions of event concepts in the deductive system intended here.

$$(\forall x,y)\ \mathrm{fetch}(x,y) \supset_{-4} \mathrm{carry}(x,y) \quad (10)$$

A matter, usually referred to by a noun in natural language, is to be conceptualized as a conjunction of the mental images of itself and its relations with others that in turn are to be reduced to certain loci in attribute spaces. In the formal system, a matter concept 'ψ' is introduced in such a context as (11), where 'ψ^+' and 'ψ^{++}' are to represent the conceptual images of itself and its relations with others, respectively, and in turn to be reduced to atomic locus formulas of all the attributes.

$$(\lambda z)\psi(z)\Leftrightarrow(\lambda z)\psi^+(z)\wedge\psi^{++}(z) \quad (11)$$

Whereas $\psi(z)$ must be a total description of all the attributes, for simplicity here is to be given only its important part with the symbol '%' representing its abbreviated part. The part $\psi^{+}(z)$ is given as a combination of atomic locus formulas for the Attribute Carrier 'z' without any other specific matter involved unlike the other part $\psi^{++}(z)$. For example, the matter called 'ice' can be conceptualized as (12). This reads that ice is always 0°C cold or less, is always of no vitality and melts into water (or is something from that H_2O) changes into water)'. In turn, the matter 'snow' can be conceptualized as (13), reading 'Snow is powdered ice attracted from the sky by the earth'. 'A_{28}', 'A_{39}' and 'A_{41}' refer to 'Temperature', 'Vitality' and 'Quality', respectively. The special symbol '_', defined by (14), is a variable bound by an existential quantifier but does not refer to any specific matter or so in the context while '*' and 'ϕ' represent 'always' and 'no value (or matter)', respectively, defined by (15) and (16).

$$
\begin{aligned}
&(\lambda x)ice(y) \Leftrightarrow (\lambda x)ice^{+}(z) \wedge ice^{++}(x)\\
&(\lambda x)ice^{+}(x) \Leftrightarrow (\lambda x)((\exists p,q)L(\_,x,p,q,A_{28},G_t,\_)\\
&\wedge p \leq 0°C \wedge q \leq 0°C)^{*} \wedge L^{*}(\phi,x,\phi,\phi,A_{39},G_t,\phi) \wedge \% \\
&(\lambda x)ice^{++}(x) \Leftrightarrow (\exists z,x_1)L(\_,z,x,x_1,A_{41},G_t,\_) \wedge water(x_1)\\
&(\wedge H_2O(z)) \wedge \%
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
&(\lambda x)snow(x) \Leftrightarrow (\lambda x)(\exists x_1)((L(\_,x,x_1,x_1,A_{41},G_t,\_)\\
&\Pi L(Earth,x,Sky,Earth,A_{12},G_t,\_)) \wedge powder(x_1) \wedge ice(x_1) \wedge \%
\end{aligned}
\tag{13}
$$

$$L(\ldots,\omega_i,\_,\omega_j,\ldots) \Leftrightarrow (\exists \omega)L(\ldots,\omega_i,\omega,\omega_j,\ldots) \tag{14}$$

$$\chi^{*} \Leftrightarrow (\forall [p,q])\ \chi\ \Pi\ \varepsilon([p,q]) \tag{15}$$

$$L(\ldots,\omega_i,\phi,\omega_j,\ldots) \Leftrightarrow \sim(\exists p)L(\ldots,\omega_i,p,\omega_j,\ldots) \tag{16}$$

All knowledge pieces resulted from an individual's everyday experience are inevitably subjective (to him/her), that is, not necessarily intelligible to others. In this sense, the formal system is subjective (to the author) as far as it employs (domain-specific) constants other than logical ones such as logical connectives (generally assumed to be objective). This section focuses on subjective or empirical laws, so called "postulates", of space and time in order for spatiotemporal language understanding. These postulates are to be treated as equivalents to axioms.

The postulates **P1** and **P2** state that *a matter never has different values of an attribute with a standard at a time*. These are called "Postulates of Identity in Assigned Values". **P1** is employed exclusively to detect semantic anomaly in such a sentence as "The red box is black" while **P2** is useful to detect event gaps in such a context as "Tom was in London yesterday and he is in Paris today."

The syntax of $\boldsymbol{L_{md}}$ allows Matter terms to appear at Values and Standard in order to represent their values in each place at the time and over the time-interval, respectively. This rule can be formulated as **P3** and **P4**. The postulate **P3** is to be utilized for such inference as "Mary went to Tom when he was in the garden. Therefore, Mary went to the (same) garden." while **P4** is for such inference as "Jim is taller than Tom. Tom is 2m tall. Therefore, Jim is taller than 2m."

P1. $L(x,y,p_1,q_1,a,g,k)\Pi L(z,y,p_2,q_2,a,g,k).\supset.\ p_1=p_2\wedge q_1=q_2$

P2. $L(x,y,p_1,q_1,a,g,k)\bullet L(z,y,p_2,q_2,a,g,k)\supset.\ q_1=p_2$

P3. $L(x_0,y,z_1,z_2,a,g,k)\Pi L(x_1,z_1,p_1,q_1,a,g,k)\Pi L(x_2,z_2,p_2,q_2,a,g,k).$
$\supset_0.L(x_0,y,p_1,q_2,a,g,k)$

P4. $L(x_0,y,p_1,p_2,a,g,z)\Pi L(x_1,z,q,q,a,g,k).\supset_0.L(x_0,y,p_1,p_2,a,g,q)$

It is quite subjective how to articulate a locus, which can be formulated as **P5** and **P6**, so called, '*Postulates of Arbitrariness in Locus Articulation*'. These postulates affect the process of conceptualization on a word based on its referents in the world and moreover they are very useful for spatiotemporal inference in such a context as "Tom flied from Tokyo to Nagoya and consecutively from Nagoya to Osaka. Therefore, he moved from Tokyo to Osaka" and "Tom moved from Tokyo to Osaka. Therefore, he passed somewhere (between the two places)", respectively.

P5. $(\forall p,q,r,k)(\exists k')L(y,x,p,q,a,g,k)\bullet L(y,x,q,r,a,g,k).\supset_0.L(y,x,p,r,a,g,k')\wedge k'\neq k$

P6. $(\forall p,r,k)(\exists q,k')L(y,x,p,r,a,g,k).\supset_0.L(y,x,p,q,a,g,k')\bullet L(y,x,q,r,a,g,k')\wedge k'\neq k$

A perceptual locus can be formulated with atomic locus formulas and temporal conjunctions such as SAND ($\wedge_0$ or Π) and CAND ($\wedge_1$ or $\bullet$). This is not necessarily the case for a conceptual locus corresponding to such a generalized mental image or knowledge piece. For example, people usually interpret the construction '*B* happens *before A* happens' as a general causality, namely, as 'If *A* happens, *B* happens *in advance*'. Whereas this should be formulated with logical connectives other than conjunctions also involved, **D1** is exclusively for perceptual loci so far as it is because there is no interpreting a negated locus formula as a locus with ***a unique time-interval*** necessary to determine a unique temporal relation τ_i.

Considering such a definition as '$A\supset B \Leftrightarrow \sim A\vee B$ $(.\equiv.\sim(A\wedge\sim B))$' in standard logic, it is not unnatural to assume 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 **D5** and its related postulates **P7** and **P8** as follows, where δ is to extract the ***suppressed*** absolute interval of a locus formula χ.

D5. $\delta(\chi)=[t_a,t_b](\in\Delta)$, where $\chi\Pi\varepsilon([t_a,t_b])$.

P7. $\delta(\sim\alpha)=\delta(\alpha)$, where α is an atomic locus formula.

P8. $\delta(\chi)=[t_{min}, t_{max}]$, 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 postulates lead to **T1** (Theorem of absoluteness of time passing) below. This theorem can read that absolute time passes during an *objective* event whether it may be perceived *subjectively* as χ or as $\sim\chi$.

T1. $\delta(\sim\chi)=\delta(\chi)$

(Proof) According to **P7** and **P8**, the time-interval of each atomic locus formula involved in χ is negation-free and therefore so is for $[t_{min}, t_{max}]$ of $\delta(\chi)$. **[Q.E.D.]**

The counterpart of the contrapositive in standard logic (i.e. A⊃B.≡.~B⊃~A) is given as **T2** (Tempo-logical Contrapositive) 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 '→' or '↔' for entailment (left-to-right or bi-directional).

T2. $\chi_1\supset_i\chi_2.\equiv.\sim\chi_2\supset_{-i}\sim\chi_1$

(Proof)

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

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

T1: $\leftrightarrow (\sim\chi_2\supset\sim\chi_1)\wedge\tau_i(\sim\chi_1,\sim\chi_2)$

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.]**

Therefore, S3 and S4 are proved to be paraphrases each other by employing **T2** while S5 and S6 are proved so by the definition of tempological conjunctions (i.e. $\wedge_i$).

(S3) It gets cloudy *before* it rains.
=If it rains, it gets cloudy *in advance*. (≡Raining$\supset_{-5}$Getting_Cloudy)

(S4) It does not rain *after* it does not get cloudy.
=Unless it gets cloudy, it does not rain *later*. (≡~Getting_Cloudy $\supset_5$ ~Raining)

(S5) It got cloudy *before* it rained. (≡Raining$\wedge_{-5}$Getting_Cloudy)

(S6) It rained *after* it got cloudy. (≡Getting_Cloudy$\wedge_5$Raining)

All loci in attribute spaces are assumed to correspond one to one with movements or, more generally, temporal events of the FAO. Therefore, the L_{md} expression of an event is compared to a movie film recorded through a floating camera because it is necessarily grounded in FAO's movement over the event. And this is why S7 and S8 can refer to the same scene in spite of their appearances, where what 'sinks' or 'rises' is the FAO and whose conceptual descriptions are given as (17) and (18), respectively, where 'A_{13}', '↑' and '↓' refer to the attribute 'Direction' and its values 'upward' and 'downward', respectively.

(S7) The path *sinks* to the brook.
(S8) The path *rises* from the brook.

$$(\exists y,z,p)L(\_,y,p,z,A_{12},G_s,\_)\Pi L(\_,y,\downarrow,\downarrow,A_{13},G_s,\_)\wedge path(y)\wedge brook(z)\wedge z\neq p \quad (17)$$

$$(\exists y,z,p)L(\_,y,z,p,A12,G_s,\_)\Pi L(\_,y,\uparrow,\uparrow,A_{13},G_s,\_)\wedge path(y)\wedge brook(z)\wedge z\neq p \quad (18)$$

Such a fact is generalized as **P9** (*Postulate of Reversibility of Spatial Event (PRS)*), where χ_s and χ_s^R are a perceptual locus and its 'reversal' for a certain spatial event, respectively, and they are substitutable with each other because of the property of '$\equiv_0$'. This postulate can be one of the principal inference rules belonging to people's common-sense knowledge about geography.

P9. $\chi_s^R .\equiv_0. \chi_s$

Any matter is assumed to consist of its parts in a structure (i.e. spatial event), which is generalized as **P10** (*Postulate of Partiality of Matter*) here, reading that a matter x_1 can be perceived or deemed as a complex of matters x_2 and x_3.

P10. $L(y,x_1,p,q,a,G_s,k)\bullet L(y,x_1,q,r,a,G_s,k) .\equiv_0. L(y,x_2,p,q,a,G_s,k)\Pi L(y,x_3,q,r,a,G_s,k)$

This postulate and **P9** are utilized for translating such a paradoxical sentence as "The Andes Mountains run north and south." into such a plausible interpretation as "One part of the Andes Mountains runs north (from somewhere) and the other part runs south".

3 Conclusions

The deductive system is one kind of applied predicate logic (i.e., pure predicate logic with certain domain-specific constants [14, 17-19]), but the domain-specificity in its syntax and semantics is exclusively related to atomic locus formulas and the essential part of its semantics is subject to their interpretation controlled by the family of domain-specific constants, namely, Attributes, Values, Patterns and Standards intended to correspond well with human sensory systems. The author has found the implementation so far a success and come to have such a perspective that the scheme presented here is applicable to various mind models for humans or humanoid robots of different competences and performances simply by controlling such a family [20]. The expressive power of $\boldsymbol{L_{md}}$ was demonstrated with linguistic or pictorial manifestations throughout this paper. Its most remarkable point in comparison with other KRLs resides in that it can provide terms of the physical world such as *carry*, *snow*, etc. with precise semantic definitions that are normalized by atomic locus formulas and visualized as loci in attribute spaces in both temporal and spatial extents (i.e. temporal and spatial events), which leads to good computability and intuitive readability of $\boldsymbol{L_{md}}$ expressions. Future work will include further elaboration and validation of the formal system and the most important problems remaining unsolved are how to provide each attribute space and how to build its corresponding atomic performance. These problems concern neuroscience as well as psychology and therefore the author will consider employment of soft computing theories such as neural network, genetic algorithm, fuzzy logic, etc. for their self-organization in the near future.

At last of this paper, the author would like to acknowledge that this work was partially funded by the Grants from Computer Science Laboratory, Fukuoka Institute of

Technology and Ministry of Education, Culture, Sports, Science and Technology, Japanese Government, numbered 14580436 and 17500132.

References

1. Yokota,M.: An Approach to Natural Language Understanding Based on Mental Image Model. In Sharp,B. (ed.), Natural Language Understanding and Cognitive Science. INSTICC PRESS (2005) 22-31.
2. Yokota,M.& Capi,G.: Cross-media Operations between Text and Picture Based on Mental Image Directed Semantic Theory. WSEAS Trans. on Information Science and Applications, 10-2 (2005)1541-1550.
3. Coradeschi,S. & Saffiotti,A.: An introduction to the anchoring problem. Robotics and Autonomous Systems, 43 (2003) 85–96.
4. Drumwright,E. Ng-Thow-Hing,V. & Mataric,M.J.: Toward a vocabulary of primitive task programs for humanoid robots. Proceedings of International Conference on Development and Learning *(*ICDL*)*, Bloomington, IN (May 2006).
5. Woods,W.A.: What's in a Link: Foundations for Semantic Networks. In Representation and Understanding, Studies in Cognitive Science. New York: Academic Press (1975) 35-82.
6. Dorr,B.& Bonnie,J.: Large-Scale Dictionary Construction for Foreign Language Tutoring and Interlingual Machine Translation. Machine Translation, 12-4 (1997) 271-322.
7. Zarri,G.P.: NKRL, a Knowledge Representation Tool for Encoding the Meaning of Complex Narrative Texts, Natural Language Engineering. Special Issue on Knowledge Representation for Natural Language Processing in Implemented Systems, 3 (1997) 231-253.
8. Lenat, D.: CyC: A Large-Scale Investment in Knowledge Infrastructure, Communications of the ACM (1996).
9. Leisi,E.: Der Waltinhalt-Seine Struktur im Deutschen und Englischen-, Quelle & Meyer, Heidelberg (1961).
10. Noton,D.: A Theory of Visual Pattern Perception, IEEE Trans. on Systems Science and Cybernetcs, SSC-6,4 (1970) 349-357.
11. Gardenfors,P: Conceptual Space, MIT Press (2000).
12. Langacker,R.: Dynamicity, fictivity, and scanning: The imaginative basis of logic and linguistic meaning. In Precher, Diane and Rudolf A. Zwaan (eds.), Grounding Cognition: The Role of Perception and Action in Memory, Language and Thinking. Cambridge: Cambridge University Press (2005) 164-197.
13. Roget,P.: Thesaurus of English Words and Phrases, J.M.Dent & Sons Ltd., London (1975).
14. McDermott,D.V.: A temporal logic for reasoning about processes and plans. Cognitive Science, 6 (1982) 101-155.
15. Allen, J.F.: Towards a general theory of action and time. Artificial Intelligence, 23-2 (1984) 123-154.
16. Shepard, R.& Metzler. J.: Mental rotation of three dimensional objects. Science, 171(972): 701-3 (1971).
17. Shoham,Y.: Time for actions: on the relationship between time, knowledge, and action. Proceedings of IJCAI\89, Detroit, MI (1989) 954-959.
18. Kabanza,F., 1995. Synchronizing multiagent plans using temporal logic specifications, Proceedings of 1st International Conf. on Multi-Agent Systems (ICMAS-95), pp.217-224.
19. Haddawy,P.: A logic of time, chance, and action for repesenting plans. Artificial Intelligence, 80-2 (1996) 243-308.
20. Shiraishi,M, Capi,G.& Yokota,M.: Human-robot communication based on a mind model. Artificial Life and Robotics (2005) 136-140.