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

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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...
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 (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 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 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. 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 L_{md} for the deductive system are listed as (i)-(ix) below. These symbols are possibly subscripted just like A_{01}, G_{x}, etc.

(i) logical connectives: \neg, \land, \lor, \supset, \equiv
(ii) quantifiers : \forall, \exists
(iii) auxiliary constants : ., (, )
(iv) sentence variables : \chi
(v) predicate variables : \psi
(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: \(L, =, \neq, >, <\) (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: \(\iff, \rightarrow, \leftrightarrow\) (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 \(\text{‘}L\text{’}\) 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 \(\text{‘}L\text{’}\) is such a seven-place predicate as is given by expression (1).

\[
L(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6, \omega_7) \tag{1}
\]

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) \(\omega_1\) is a matter term (variable or constant)
(b) \(\omega_2\) is a matter term
(c) \(\omega_3\) is a value or a matter term
(d) \(\omega_4\) is a value or a matter term
(e) \(\omega_5\) is an attribute term
(f) \(\omega_6\) is a pattern term
(g) \(\omega_7\) is a standard (or matter) term

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

“Matter \(\omega_1\) causes Attribute \(\omega_5\) of Matter \(\omega_2\) to keep \((\omega_3 = \omega_4)\) or change \((\omega_3 \neq \omega_4)\) its values temporally \((\omega_6 = G_t)\) or spatially \((\omega_6 = G_s)\) over a certain absolute time-interval, where the values \(\omega_3\) and \(\omega_4\) are relative to the standard \(\omega_7\).”

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.
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 $\omega_2$) 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 `∧`, disjunction `∨`, implication `⊃` and equivalence `≡`) unlike the conventional ones exclusively for the conjunction [14, 15]. The definition of a tempo-logical connective $C_i$ is given by $D_1$, where $\tau$, $\chi$ 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 `∧', respectively. The definition of each $\tau_i$ 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 (=\&\_)$ but not for pure `temporal relations (=\&\_)$'. The TLCs used most frequently are `SAND ($\&\_0$)' and `CAND ($\&\_1$)', standing for `Simultaneous AND' and `Consecutive AND' and conventionally symbolized as `\Pi' and `•', respectively.
D1. \( \chi_1 \land \chi_2 \land \tau_i(\chi_1, \chi_2) \land \tau_i(\chi_2, \chi_1) (\forall i \in \{0, \pm 1, \pm 2, \pm 3, \pm 4, \pm 5, \pm 6\}) \)

In order for explicit indication of absolute time elapsing, ‘Empty Event’ denoted by ‘\( \varepsilon \)’ is introduced as D2 with the attribute ‘Time Point (A34)’ and the Standard of absolute time ‘\( K_T \)’, where R and \( \Delta \) 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 \( L_{med} \).) According to this scheme, the suppressed absolute time-interval \([t_a, t_b]\) of a locus \( \chi \) can be indicated as (4).

D2. \( \varepsilon([t_i, t_j]) \land (\exists x, y, g) L(x, y, t_i, t_j, A34, g, K_T) \)

where \([t_i, t_j] \in \Delta = \{(t_1, t_2) | t_1 < t_2, t_1, t_2 \in R\}\)

\( \chi \Pi \varepsilon([t_a, t_b]) \) (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 \( \chi_1 \) 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. \( (\chi_1 \pi \chi_2)^R \iff \chi_2^R \pi \chi_1^R \)

\( L^R(x, y, p, q, a, g, k) \iff L(x, y, q^R, p^R, a, g, k) \)

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 \( \chi \).

D4. \( \chi^n \iff \chi \quad (n=1) \)

\( \chi^n \iff \chi \chi^{n-1} \quad (n>1) \)

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 temporal conjunctions (i.e. \( \land \)) with the abstraction operator ‘\( \lambda \)’. 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 abbrevia-
tion (9) where Event Causers (i.e. the matters at \( o_1 \)) 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 (A12)’ [1,2].

\[
\begin{align*}
&\lambda x, y \text{carry}(x, y) \iff \lambda x, y \text{convey}(x, y) \iff \lambda x, y (\exists p, q, k) L(x, x, p, q, A_{12}, G_{k})_{x=y \wedge p \neq q} \\
&\lambda x \text{shuttle}(x) \iff \lambda x (\exists p, q, k) (L(x, x, p, q, A_{12}, G_{k}) \land p \neq q \land n \geq 1) \\
&\lambda x, y \text{fetch}(x, y) \iff \lambda x, y (\exists p_1, p_2, k) L(x, x, p_2, p_1, A_{12}, G_{k}) \land (L(x, x, p_1, p_2, A_{12}, G_{k}) \land x \neq y \land p_1 \neq p_2) \\
&\lambda x, y, z \text{hand}(x, y, z) \iff \lambda x, y, z (\exists k) L(x, y, x, z, A_{12}, G_{k}) \land (x \neq y \land y \neq z \land z \neq x) \\
&\iff \lambda x, y, z (\exists k) L\{x, z\} \land x \neq y \land y \neq z \land z \neq x.
\end{align*}
\]

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 ‘\( \supseteq_{4} \)’ is the ‘implication (\( \supseteq \))’ furnished with the temporal relation ‘finished-by (\( \tau_{4} \))’. This kind of formula is not an axiom but a theorem deducible from the definitions of event concepts in the deductive system intended here.

\[
(\forall x, y) \text{fetch}(x, y) \supseteq_{4} \text{carry}(x, y)
\]

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 ‘\( \psi \)’ is introduced in such a context as (11), where ‘\( \psi \)’ and ‘\( \psi^{+} \)’ 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.

\[
\lambda z \psi(z) \iff (\lambda z) \psi^{+}(z) \land \psi^{+}(z)
\]
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 H2O) 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'. 'A28', 'A39' and 'A41' 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 '$\phi$' represent 'always' and 'no value (or matter)', respectively, defined by (15) and (16).

\begin{align*}
(\lambda x)\text{ice}(y) & \equiv (\lambda x)\text{ice}'(z) \land \text{ice}''(x) \\
(\lambda x)\text{ice}'(x) & \equiv (\lambda x)((3p,q)L(_,x,p,q,A28,G_{n-}) \land p\leq 0°C \land q\leq 0°C)* \land L*(\phi,x,\phi,A39,G_{n},\phi) \land % \\
(\lambda x)\text{ice}''(x) & \equiv (\exists x1)L(_,x1,x1,A41,G_{n-}) \land \text{water}(x1) \\
\land H2O(x) \land % & \\
(\lambda x)\text{snow}(x) & \equiv (\lambda x)(\exists x1)((L(_,x1,x1,A41,G_{n-}) \land \text{powder}(x1)) \land \text{ice}(x1) \land % \\
\land L(\text{Earth},x,\text{Sky},\text{Earth},A12,G_{n-}) &
\]

\begin{align*}
L(\ldots,\omega_i,\phi,\omega_j,\ldots) & \equiv (\exists \omega) L(\ldots,\omega,\omega,\omega,\ldots) \\
\chi^* & \equiv (\forall [p,q]) \chi \Pi \varepsilon([p,q]) \\
L(\ldots,\omega_i,\phi,\omega_j,\ldots) & \equiv (\exists p)L(\ldots,\omega,\omega,\omega,\ldots)
\end{align*}

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 $L_m$ 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. \[ L(x,y,p_1,q_1,a,g,k) \land L(z,y,p_2,q_2,a,g,k) \supseteq p_1 = p_2 \land q_1 = q_2 \]

P2. \[ L(x,y,p_1,q_1,a,g,k) \land L(z,y,p_2,q_2,a,g,k) \supseteq q_1 = p_2 \]

P3. \[ L(x_0,y,z_1,z_2,a,g,k) \land L(x_1,z_1,p_1,q_1,a,g,k) \land L(x_2,z_2,p_2,q_2,a,g,k). \supseteq L(x_0,y,p_1,q_2,a,g,k) \]

P4. \[ L(x_0,y,p_1,p_2,a,g,z) \land L(x_1,z,q,q,a,g,k). \supseteq L(x_0,y,p_1,p_2,a,g,q) \]

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 flew 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. \[ (\forall p,q,r,k)(\exists k')L(y,x,p,q,a,g,k) \land L(y,x,q,r,a,g,k). \supseteq L(y,x,p,r,a,g,k') \land k' \neq k \]

P6. \[ (\forall p,r,k)(\exists q,k')L(y,x,p,r,a,g,k). \supseteq L(y,x,p,q,a,g,k') \land L(y,x,q,r,a,g,k') \land k' \neq k \]

A perceptual locus can be formulated with atomic locus formulas and temporal conjunctions such as SAND (\& or \Pi) and CAND (\& or \&). 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 \(\tau\).

Considering such a definition as ‘A \(\supset\) B \(\equiv\) \neg A \lor B \(=\) \neg(A \land \neg 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 \(\delta\) defined by D5 and its related postulates P7 and P8 as follows, where \(\delta\) is to extract the suppressed absolute interval of a locus formula \(\chi\).

D5. \[ \delta(\chi) = [t_{\min}, t_{\max}] \in \Delta, \text{ where } \chi \Pi \varepsilon([t_{\min}, t_{\max}]). \]

P7. \[ \delta(\neg \alpha) = \delta(\alpha), \text{ where } \alpha \text{ is an atomic locus formula.} \]

P8. \[ \delta(\chi) = [t_{\min}, t_{\max}], \text{ where } t_{\min} \text{ and } t_{\max} \text{ are respectively the minimum and the maximum time-point included in the absolute time-intervals of the atomic locus formulas, either positive or negative, within } \chi. \]
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 $\chi$ 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 $\chi$ 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. $A \supset B \equiv \sim B \supset \sim A$) 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 metasymbol $\rightarrow$ or $\leftrightarrow$ for entailment (left-to-right or bi-directional).

T2. $\chi_1 \supset \chi_2 \equiv \sim \chi_2 \supset \sim \chi_1$

(Proof)

D1: $\chi_1 \supset \chi_2 \leftrightarrow (\chi_1 \supset \chi_2) \land \tau(\chi_1, \chi_2)$

PL: $\leftrightarrow (\sim \chi_2 \supset \sim \chi_1) \land \tau(\chi_1, \chi_2)$

T1: $\leftrightarrow (\sim \chi_2 \supset \sim \chi_1) \land \tau(\sim \chi_2, \sim \chi_1)$

D1: $\leftrightarrow \sim \chi_2 \supset \sim \chi_1$ [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. $\land$).

(S3) It gets cloudy before it rains.

=If it rains, it gets cloudy in advance. (=Raining $\supset$ Getting_Cloudy)

(S4) It does not rain after it does not get cloudy.

=Unless it gets cloudy, it does not rain later. (=~Getting_Cloudy $\supset$ ~Raining)

(S5) It got cloudy before it rained. (=Raining $\land$ Getting_Cloudy)

(S6) It rained after it got cloudy. (=Getting_Cloudy $\land$ 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 ‘$A_{13}$’, ‘$\uparrow$’ and ‘$\downarrow$’ 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.

$\exists y, z, p) L(_, y, p, z, A_{13}, G_{n}) \Pi L(_, y, \downarrow, A_{13}, G_{n}) \land \text{path}(y) \land \text{brook}(z) \land z \neq p$  (17)

$\exists y, z, p) L(_, y, z, p, A_{12}, G_{n}) \Pi L(_, y, \uparrow, A_{13}, G_{n}) \land \text{path}(y) \land \text{brook}(z) \land z \neq p$  (18)
Such a fact is generalized as **P9** (*Postulate of Reversibility of Spatial Event (PRS)*), where $\chi_s$ and $\chi_s^R$ 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.** $L(y,x_1,p,q,a,G_s,k) \ast L(y,x_1,q,r,a,G_s,k) \equiv 0 \ast L(y,x_2,p,q,a,G_s,k) \Pi L(y,x_3,q,r,a,G_s,k)$

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 $L_{md}$ 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 $L_{md}$ 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.

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