# Computational Theory of Perceptions

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## ABSTRACT

This paper aims to bring out the significant contribution of the Professor Lotfi A.Zadeh,"the father of Fuzzy Logic" in the field of Soft Computing. The computational Theory of Perceptions (CTP) deals with the automated processing of human knowledge expressed in Natural language. The development of computational system based on the Computational Theory of Perceptions is a challenging task that requires taking into account knowledge extended to several scientific disciplines such as Fuzzy Logic, Linguistics and Software Engineering. The Computational Theory of Perceptions is based on the methodology of computing with words. In CTP words play the role of labels of perceptions and more generally, perceptions are expressed as propositions in a natural language. Computing with words (CW)- based techniques are generally used to translate propositions expressed in a natural language into Generalized Constraint Language (GCL).

## 1. INTRODUCTION

### 1.1 Definition of a Fuzzy Set

A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one. The notions of inclusion, union, intersection, complement, relation, convexity, etc are extended to such sets, and various properties of these notions in the context of fuzzy sets are established. In particular, a separation theorem for convex fuzzy sets is proved without requiring fuzzy sets be disjoint.

### 1.2 Generalized Constraint Language

A generalized constraint is a constraint of the form $X$ isr $R$, where $X$ is the constrained variable, $R$ is a constraining relation, generally non-bivalent, and $r$ is an indexing variable which identifies the modality of the constraint, that is, its semantics. The principal constraints are: possibilistic ($r$=blank); probabilistic ($r=p$); veristic ($r=v$); usuality ($r=u$); random set ($r=rs$); fuzzy graph ($r=fg$); bimodal ($r=bm$); and group ($r=g$). Generalized constraints may be qualified, combined and propagated. The set of all generalized constraints together with rules governing qualification, combination and propagation constitutes the Generalized Constraint Language (GCL).

### 1.3 Computational use of Natural Language

NL has evolved in parallel with the human brain as a product of natural evolution. NL is not the result of the rational design of human beings as is the case of Mathematics or Music Notation. NL is a dynamic system that cannot be explained simply as the sum of its parts .Typically, we do not use a set of formal rules to produce our NL utterances. We could say that a human speaker produces his/her discourse following a chaotic procedure similar to the one used by a tree to build branches and leaves.

Taking the perspective of the developer of CTP applications let us briefly analyze the two complementary functions of language: construing experience and enacting social processes.

### 1.4 Experience

Regarding the first function, in agreement with Systemic Functional Linguistics (SFL), NL is a resource with which human beings construct the mental maps of their phenomenal world, of their experience of process: what goes on out there and what goes on in the realms of their own consciousness. The experience is a resource of meaning, a potential of under-standing, representing and acting on the world. The particulars of our daily life make sense because they are instantiations of this potential. The experience includes descriptions of two layers of reality: First order phenomena related directly with the environment and the second order phenomena formed of the meanings and wordings that perceptions of first order phenomena bring into being .

During the last thousands of years, human evolution has been supported not only by genetic transmission but essentially by cultural learning . It is well known that, in this process, the invention of the printing press produced a revolutionary push. During recent decades, computers have acquired an important role as a medium of storing and processing information boosting this process, i.e. computers and the Internet are used as the new encyclopedia.
But we believe computers will have a more important role as contributors to mankind evolution. The next challenge consists of using computers as a tool where NL does not have the general meaning provided in an encyclopedia but the particular meaning that a specific user, with a specific personal experience, requires in a specific context of use.

The achievement of this goal will convert computers into personal assistants, into personalized tools to help us to go far in the construction of our personal experience, i.e. in our personal understanding of the world.

From the perspective of computational systems developers, we will use the term "World Model" for a computational representation of reality, a representation of the context where the computer must perform its function. We can see this World Model as a projection of the programmer's experience into the computer memory.

## 2. HUMAN COMPUTER INTERFACE

Regarding the second function of NL, enacting social processes, the computer can be considered as a new type of partner in the NL communication process typically performed between human beings.

When using a computer with this role, we must consider three modes to communicate meaning with NL

1.The domain of language of the computational application. We should use the concepts and associated words of the culturally recognized repertory of social practices and concerns. Moreover, we should take into account the personal use of NL, i.e. the personal experience of the specific user at whom the application is aimed.

2.The relationship established between user and computer. When using NL we should use the culturally recognized repertory of role relationships and interactive patterns corresponding with a specific speaker - listener relationship. We should choose and design the role the user expects to be adopted by the computer. That is to say, we must assign the computer the role of "secretary", "weather broadcast speaker", or perhaps a new type of role that still should be carefully de-signed and explained.

3.It is important to realize that, when humans communicate, they establish a theory about the mind of the other, about the other's experience and intentions, which is absolutely relevant to interpret of the meaning of the NL utterances

4.The mode of expression. We must consider both, the medium (written, spoken) and the rhetorical function (persuasive, didactical, informative, etc.) of the language used. Additionally, we should consider the possibility of complementing the use of NL with graphics and sounds, and the possibility of expressing emotions with the tone of voice and the face expressions of an avatar.

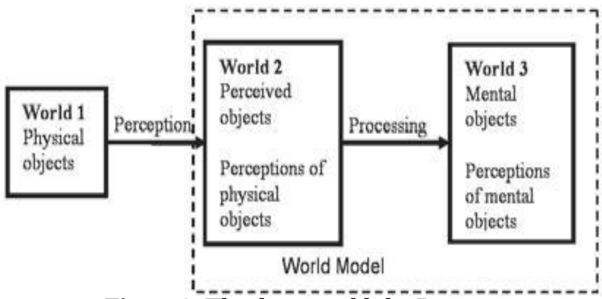



**Figure 1: The three worlds by Popper.**

In agreement with Popper, we can distinguish three worlds: The first is the unknown world of what is going on out there, i.e. the world of the objects in our environment; the second is the world of the perceived objects, i.e. the world of information that we acquire thanks to our senses; and the third is the world of the mental objects that we create in the realm of our consciousness, i.e. they are abstract objects built using NL and that constitute an important part of our Experience (See Fig. 1)

In our approach we can say that we construe our experience using perceptions. Moreover we can say that, remembering or figuring out a mental object is a form of perception. This is because NL is basically a system for describing perceptions .

If we define *to perceive* as: "to attain awareness or understanding of elements in the environment" then we can say that *to perceive using a computational system* is: the process per-formed using a computer to obtain information and to produce a representation useful to the system designer, and therefore for the human operator, to attain awareness or understanding of elements in the environment".

Therefore the programmer and the final user of the computational system are the interpreters of the information provided by the computer. The human uses the computer as a tool to perceive the reality in a comparable way that he/she uses a clock to kn of bacteria in a drop of water.

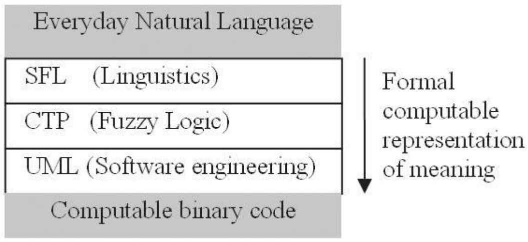



**Figure 2: CTP occupies a position between Linguistics and Software Engineering**

### 2.1 Granule

#### *2.1.1 In CTP, granules are used to describe perceptions.*

*The b*asic unit of meaning is a granule. A granule is a clump of elements which are drawn together by indistinguishability, similarity, proximity or functionality.

The perception of an object can be described either only as a granule, or composed by a collection of granules. A granule is a node in a network of relations with other granule. The granularity of the description of objects allows us to deal with real world problems considering different degrees of detail. For example, we summarize the description of an object by hiding the irrelevant granules and remarking on the relevant ones. Indeed, in this sense, the description of an object, i.e. a perception, is always a summary.

Fig. 2 shows three disciplines devoted to NL meaning representation where CTP occupies a relevant position between Linguistics and Software Engineering. Linguistics is needed to face the complexity of a normal conversation, a tale, etc. Unified Modeling Language (UML) is a language developed in Software Engineering during the last decades to develop computational models of reality and it is a type of tool needed when we deal with the development of complex computational applications.

In SFL the basic unit of meaning is a *figure* (figure with the meaning of understanding of the verb figure out). A figure has three types of elements: participants, processes and circumstances.

In UML the basic unit of meaning is a *class*. A class has associated attributes and operations.

Figures and classes are types of granule and we can use them to computationally describe perceptions.

### *2.1.2 Information as Constraint*

In CTP, granules have fuzzy attributes, i.e. the borders of a granule are fuzzy. Fuzziness of granules, their attributes and their values allow us to model the way in which human concepts are formed, organized and manipulated.

Granules are defined using fuzzy constraints on the possible values of their attributes. In this sense, in CTP information is expressed as a set of constraints. The elasticity of constraints is obtained by using Fuzzy Logic to define them. This elasticity is intended to be a reflection of the same elasticity found in the meaning of words in NL.

### *2.1.3 Computational Perception*

As mentioned above, a computational perception (perception for short) is a representation of the information obtained about an object with a level of granularity useful for the programmer's purposes.

In CTP there are two different ways of describing a perception: on the one hand using NL and on the other hand using a formalized language which computers can process.

The first description is the natural way of describing the world. NL has evolved with the human being acquiring capacity to understand and communicate complex world descriptions , i.e. NL contains all the required resources to describe the objects that we can perceive or imagine, their properties and be-haviour.

The second description is a challenge that still lacks of a general solution. It consists of a formalized computable representation with equivalent meaning to the NL propositions. In CTP this language is named Generalized Constraint Language (GCL) .

A key element of GCL is the concept of linguistic variable . The values of a linguistic variable are granules. Assigning value to a linguistic variable consists of defining a constraint on the set of its possible values.
In GCL the meaning of a proposition p is expressed as:

*XisrR*

where

- *X* is the constrained linguistic variable whose structure of values ranges from the simple linguistic label required to represent a perception associated with the value of a sensor to a complex structure of information, namely, a vector of propositions, a fuzzy graph, a function, etc.

- *R* is the constraining relation

- *isr* is a copula in which *r* is a variable indicating the type of constraint. Primary constraints are formalizations of three basic perceptions: perception of possibility; perception of likelihood; and perception of truth.

## 3. PRECISIATION

Granularity allows us to order perceptions by their meaning. At one extreme we have the set of all possible meanings and at the other extreme a simple text with a the meaning of a specific perception, i.e. using constraints we construe a text as an instance of the whole available potential of meaning.

Precisiation consists of aggregating constraints until a description is provided of a perception useful for a specific propose. Precisiation is a form of modelling perceptions by aggregating constraints .

As mentioned above we can see experience as a network of interrelated granules. We describe a perception by defining a sub-network of related granules. Precisiation requires determining a level of granularity, i.e. the composition of this sub-network.

From a practical point of view, one important relation, that we could consider the first in the Precisiation process, is the relation "a type of". This relation organizes the potential of meaning into the hierarchal order of Instantiation - Generalization.

Once determined the position of the perception in this dimension we can continue introducing constraints in other dimensions depending on every specific application such as: "is part of", "causality", "dependency", etc.

In SFL this network of interrelated granules is called a Sys-tem Network. A System Network is an acyclic directed graph, consisting of elements of meaning partially ordered in hierarchies using relations of meaning .

## 3.1 Levels of Precisiation

Precisiation is a multidimensional process and the ranking is continuous rather than discrete, i.e. there are so many levels of Precisiation as practical uses of NL. From the practical point of view of organizing the design of a computational system based on CTP we have defined the hierarchy of levels represented in Fig. 3.

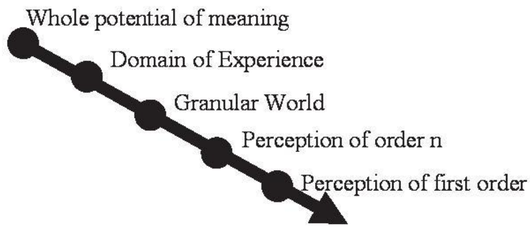



**Figure 3: A hierarchy of levels of precisiation**

### *3.1.1 Domain of Experience/Language*

This first level of Precisiation consists of delimiting a Domain of Experience. A Domain of Experience is a closed domain where the process we like to describe takes place. A Domain of Experience defines a specific context, a set of possible situations and corresponds with a Domain of Language. The Concept of Domain of Language is related with the concept of language-games by Wittgenstein .

A Domain of Language contains a subset of possible meanings; each domain has associated a corpus of NL expressions and linguistic patterns. They are at intermediate level in the ordered structure of granularity. For example, the "language of cooking" is an instantiation of the "whole language", the "language of cooking deserts" is a finer level of instantiation, and "the language of cooking apple cakes" is even a more de-tailed instantiation.

## 4. GRANULAR WORLD

A Granular World (GW) contains a subset of meanings be-longing to a Domain of Experience.

In our approach this is a quite technical concept taken from

Control Theory. We can see GW as an n-dimensional State Space where we must define the needed variables and procedures to create a computational model of the system we want to describe.

A basic element of a GW is the Vector of Linguistic State Variables (SV). Every perception in a GW can be described as a combination of constraints on the possible values of these variables. The application of Fuzzy Logic in Systems Theory was introduced by Zadeh several decades ago .

Complex perceptions in a GW are granules built with sets of lower order granules. In a GW the explanation of a perception is a set of more detailed perceptions that describes its meaning with deeper degree of granularity.

The variables belonging to SV provide the most detailed possible explanation of a perception in a GW.

## 4.1 Perception of First Order

Perception of first order ($p^1$) in a computational system is a perception directly associated with the value provided by a sensor at an instant in time.

The basic form of a perception of first order is a proposition that describes the subjective value of a measure, e.g. "The temperature is High" is a subjective description, i. e. for a specific user in a specific use, when the sensor measure reads 45$^o$C.

There are two forms of representing $p^1$: The linguistic representation, e.g.:

$p^1$: "The Temperature is High"

And the formal representation:

$p^1$: $X = \mu_{Ai}(x)$

where:

$X$ is a linguistic variable (e.g. Temperature).

- $A_i$ is a linguistic term belonging to the set of possible linguistic values of $X$ (e.g. {Low, Medium, High}).

- $\mu_{Ai}(x)$ is the membership function associated with the linguistic term $A_i$.

- $x$ is a numerical value obtained from the sensor (e.g. 45$^o$C).

We say that the meaning of a perception of first order $p^1$ can be *explained* using numerical values obtained from sensors and a set of membership functions that covers the domain of these possible values. Because perceptions of the first order work directly upon sensor values, we say these perceptions constitute the most detailed linguistic description of a signal, i.e. it has the finest granularity. Obviously, the linguistic variables associated with first order perceptions are good candidates to belong to the SV of a GW.

## 4.2 Perception of First Order n

Granularity of perceptions allows us to create a hierarchy describing complex perceptions using sets of more detailed ones. For example, two first order propositions

$p^1_1$: "The Temperature is Warm" and
$p^1_2$: "The Humidity is Medium"

could be used to explain the meaning of $p^2$: "The Room is Comfortable".

Typically this explanation has the form of a rule: IF $p^1_1$ AND $p^1_2$ THEN $p^2$.

We could extend easily this example by considering other perceptions such as "Acoustic noise" or "Number of persons in the room" to construe the *explanation* of a more complex n-order perception of Comfort.

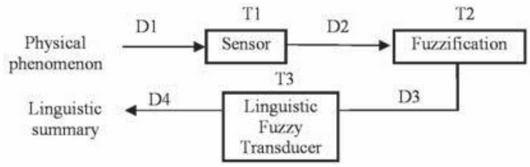



**Figure 4: A chain of transducers (T) to translate between several Domains of Language (D).**

Linguistic Fuzzy Transducer

## 5. LINGUISTIC FUZZY TRANSDUCER

In our context a Linguistic Fuzzy Transducer is a computational system capable of translating between two different representations of a perception.

Humans are good translators between perceptions described in different domains of language, e.g. when a teacher explains his matter he is translating his perceptions to the domain of language that he expects the students have. A system with the capacity of translating between two natural languages is a transducer. A question answering system could be considered as a transducer with the capacity of providing detailed explanations of a given perception. A system with the capacity of summarize information is a transducer.
Unfortunately to build a computational version of a Linguistic Transducer is still a challenge without a general solution. Fig. 4 shows a sequence of transducers which convert a perception of the physical environment into representations in different domains of language with different levels of granularity. Indeed, the figure represents a family of computational systems with the capacity of generating a linguistic summary of data provided by sensors. D1 is the domain of language of Physics, D2 is the domain of numerical values provided by sensors, D3 is essentially a domain of first order perceptions obtained after a process of fuzzification and D4 is the domain of language where the final user will use the information.

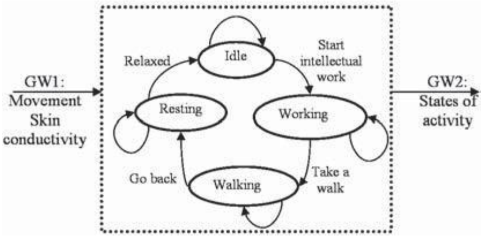
A Linguistic Fuzzy Transducer has the following basic elements:

- GW1: The Granular World of the input represented by its associated SV1.

- GW2: The Granular World of the Output represented by its SV2.

- Linguistic Fuzzy Model: A model is a simplification of reality constructed using our perceptions. Usually we need to analyze the system at different levels of granularity to understand its functioning. In Fuzzy Logic this type of model is called Linguistic Fuzzy Model that typically can be implemented as a set of fuzzy rules that control the system evolution in time. .

The rest of this section describes a simple example of the type of computational system represented in Fig. 4.




This experiment has been performed in the setting of the daily routine of a person dedicated to sedentary work: reading, writing and managing a computer in an office environment. A typical situation that we would like to model is the following:

1. The subject starts his/her day relaxed at the desk.

2. The subject turns on the computer, reads and answers emails, reads papers, writes notes and so on.

3. Initially the subject will remain seated and tension levels rise slowly.

4. After time the tension starts to provoke difficulties in concentration. The subject starts to move in his/her chair and shows behavior such as going to the toilet or moving paperwork around the office.

5. Then the subject decides to take a small walk outside ’to clear his/her mind’.Finally the subject returns to his/her office desk and continues working, again in a less stressful state (similar to the starting point).

Fig. 5 shows a diagram that represents the evolution of the activity and state of the subject during the experiment. Note that we consider the subject able to recover part of the initial ’relaxed state’ by doing some physical exercise.

The goal consists of monitoring the physical activity, the levels of stress and mental tiredness of the subject and to create a linguistic report summarizing the temporal evolution of these parameters. This experiment provides the first steps into the development of a computational system with the objective to help the user to increase his/her effectiveness and satisfaction.

Let us see briefly how to obtain, in this case, the main components of the last transducer (T3) in Fig. 4:

GW1: The subject were wearing two sensors: A skin conductivity meter fixed attached to the left wrist, with electrodes attached to the index finger and the middle finger. The accelerometer was kept in the chest pocket of the subject’s shirt. The subject was instructed to follow the steps of the experiment as described above.

After the fuzzification process we have two fuzzy linguistic variables which constitute the vector: SV1=(Activity, Skin Conductivity).

GW2: is represented by the vector SV2=(Idle, Working, Walking, Relaxing).

LFM: We have built this LFM using a Fuzzy Finite Machine (FFSM) where the states were labeled as: $q_1$: Idle, $q_2$: Working, $q_3$: Walking and $q_4$: Relaxing. The evolution of this FFSM is controlled by the following set of fuzzy rules:

$R_{11}$: IF (Q IS $q_1$) AND (Activity IS Low) AND (Conductivity IS Low) THEN Q IS $q_1$

$R_{12}$: IF (Q IS $q_1$) AND (Activity IS Low) AND (Conductivity IS Medium) THEN Q IS $q_2$

$R_{22}$: IF (Q IS $q_2$) AND (Activity IS Medium) AND (Conductivity IS Medium) THEN Q IS $q_2$

$R_{23}$: IF (Q IS $q_2$) AND (Activity IS Medium) AND (Conductivity IS high) THEN Q IS $q_3$

$R_{33}$: IF (Q IS $q_3$) AND (Activity IS High) THEN Q IS $q_3$

$R_{34}$: IF (Q IS $q_3$) AND (Activity IS Low) THEN Q IS $q_4$

$R_{44}$: IF (Q IS $q_4$) AND (Activity IS Medium) AND (Conductivity IS High) THEN Q IS $q_4$

$R_{41}$: IF (Q IS $q_4$) AND (Activity IS Low) AND (Conductivity IS Medium) THEN Q IS $q_1$
Where $R_{ii}$ are rules to remain in the state and $R_{ij}$ are rules to change.

The output is the template of a simple report as in the following example:

“The subject started RELAXED at the desk at 0 minutes. Then the subject was working during 15 minutes without signs of tiredness. Around 25 minutes the subject was moving and appears uncomfortable. At 60 minutes the subject decided to take a walk outside and went back at 75 minutes. Around 80 minutes the subject was relaxing until to be RELAXED. About 90 minutes the subject started to work again.”

## 6. CONCLUSION

In the years to come, computing with words and perceptions is likely to emerge as an important direction in science and technology. Manipulation of perceptions and words which describe them is destined to gain in respectability. It is becoming interestingly clear that in dealing with real-world problems there is much to be gained by exploiting the tolerance for imprecision, uncertainty and partial truth. This is primary motivation for the methodology of computing with words (CW) and the computational theory of perceptions which are outlined in this paper.

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