

SOME BASIC FORMULATIONS FOR IMPLEMENTING A DIAGNOSTIC EXPERT SYSTEM BASED ON COGNITIVE MAPS

Bianvenido Jose A. Juliano, Jr.
Department of Computer Science
The Florida State University
Tallahassee, Florida 32306-4019
U. S. A.
(904) 644-2296

Wyllis Bandler
Department of Computer Science
and Institute for Cognitive Sciences
The Florida State University
Tallahassee, Florida 32306-4019
U. S. A.
(904) 644-6407

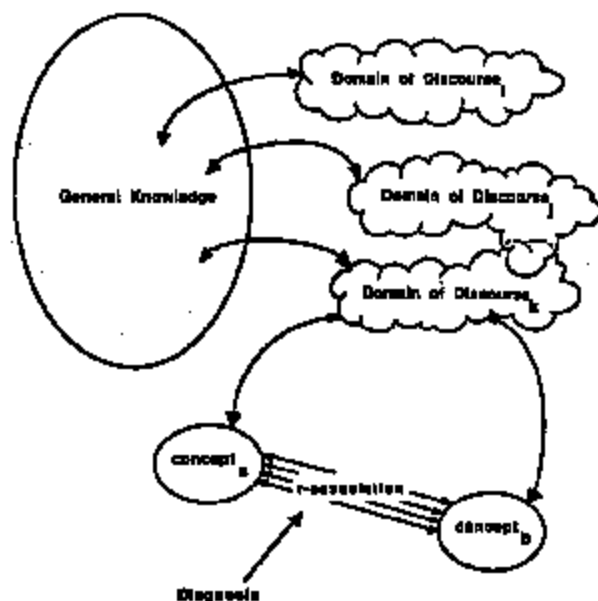


Figure 1: Preliminary notions

Abstract

This paper discusses some of the basic theoretical formulations related to an ongoing exploratory study concerning the cognitive processes involved during scientific problem solving. It presents an approach we propose that utilizes conceptual graph structures called *fuzzy cognitive maps* to approximate the novice problem solver's current *chain-of-thought*. These structures provide a cognitive model of the novice. Set-theoretic characteristics suggest an effective fault-detection scheme based on overlays, while order relations are utilized for error diagnosis. Fuzzy formulations for these conceptual structures are also presented.

1 Introduction

This study is concerned with the development of an intelligent system for diagnosing problem solving skills. Initial efforts stem from related research in the fields of education and the physical sciences. A series of extensive studies in classical genetics problem solving [10,11] is the current major reference.

These studies have resulted in the proposal [12] of an overall design for a working expert system that takes the role of an expert tutor. It incorporates a *chain-of-thought analyzer* that establishes a cognitive model of the student, to distinguish from student modeling approaches utilized by other existing intelligent tutoring systems (ITSs). In this paper, we present a solution that not only performs the diagnostic task; it suggests effective tutoring capabilities as well. We refer the reader to our preceding paper [8] that discusses the theoretical framework of our research efforts.

2 Fuzzy Cognitive Maps

The mathematical formulations presented here stem from graph theory, set theory, and relations theory. Some formulations are derived from Rosenfeld's *fuzzy graphs* [9] and from Kosko's *fuzzy cognitive maps* [8].

2.1 General Knowledge, Domains, and Concepts

Some preliminary notions are required before establishing a framework for cognitive maps designed for fault-detection and error diagnosis in scientific problem solving. The notion of *concepts* should be of primary interest in studies regarding conceptual perception of problems and their solutions. A *concept* is considered to be a set of ideas here.

The conjectured interrelationship between knowledge, domains and concepts is depicted in Figure 1. Mathematically, we refer to general knowledge as a *universe*, X . The domains of discourse are also known as *concept spaces*, $C \in \mathcal{P}(X)$. $\mathcal{P}(X)$ denotes an applicable formulation for the *power set* of X , the set of all its subsets. Concepts constitute knowledge and understanding. Clearly, any concept $c \in X$ has the property that $c \in C$, for at least one $C \in \mathcal{P}(X)$. These initial conceptions are the basis for the mathematical formulations developed here.

2.2 Fuzzy Relations on a Fuzzy Set

The following definitions of fuzzy relations on a fuzzy set are adopted from [7,9,13]. Whereas these and other papers focus on fuzzy binary relations, which is also the concern in this study, some general definitions for n -ary fuzzy relations are outlined as the basis for succeeding formulations.

Let X be a set. A fuzzy subset \tilde{S} of X is a set characterized by the mapping

$$\mu_{\tilde{S}}: X \rightarrow [0, 1] \quad (1)$$

which assigns to each element $x \in X$ a membership degree, $0 \leq \mu_{\tilde{S}}(x) \leq 1$. Another notation for a fuzzy subset \tilde{S} of X is $\tilde{S} \in [0, 1]^X$, where $[0, 1]^X$ denotes the fuzzy power set of X — the set of all fuzzy subsets of X . Similarly, an n -ary fuzzy relation \tilde{R} on X is a fuzzy subset of the product space X^n . \tilde{R} is characterized by the mapping

$$\rho_{\tilde{R}}: X^n \rightarrow [0, 1] \quad (2)$$

which assigns to each n -tuple $(x_1, x_2, \dots, x_n) \in X^n$ a relational strength, $0 \leq \rho_{\tilde{R}}(x_1, x_2, \dots, x_n) \leq 1$, which is the degree of certainty that \tilde{R} holds. In the special cases where μ and ρ can only take on the values 0 and 1, they reduce to the characteristic functions of a crisp subset of X and a crisp n -ary relation on X , respectively.

In general, given a fuzzy subset \tilde{S} of X and an n -ary fuzzy relation \tilde{R} on X , we refer to \tilde{R} as a n -ary fuzzy relation on the fuzzy set \tilde{S} if

$$\rho_{\tilde{R}}(x_1, x_2, \dots, x_n) \leq \bigwedge_i \mu_{\tilde{S}}(x_i) \quad (3)$$

where the \bigwedge_i indicates the minimum with respect to $i = 1, \dots, n$. Hence, the relational strength amongst elements of an n -tuple in \tilde{R} is not allowed to exceed their membership degrees in \tilde{S} .

The symbols " \smile " and " \searrow " will be used to denote the fuzzy extension and fuzzy restriction, respectively, of a fuzzy mapping. Let \tilde{P} be a fuzzy subset of a set X , defined as $\tilde{P}: X \rightarrow [0, 1]$. \tilde{R} is an n -ary fuzzy relation on \tilde{P} , characterized by the membership function ρ defined similarly to the fuzzy relation $\rho_{\tilde{R}}$ on \tilde{S} above. The fuzzy restriction or f -restriction of \tilde{R} on $\tilde{E} \subseteq \tilde{P}$, written $\tilde{R} \searrow \tilde{E}$, is the fuzzy n -ary relation \tilde{P} denoted by $\psi: \tilde{E}^n \rightarrow [0, 1]$, with the property that

$$\psi(x_1, x_2, \dots, x_n) = \rho(x_1, x_2, \dots, x_n) \wedge \bigwedge_i \mu_{\tilde{E}}(x_i) \quad (4)$$

for $i = 1, \dots, n$. A fuzzy extension or f -extension of \tilde{R} on $\tilde{G} \supseteq \tilde{P}$, written $\tilde{R} \smile \tilde{G}$, is the fuzzy n -ary relation \tilde{T} denoted by $\tau: \tilde{G}^n \rightarrow [0, 1]$, with the property that

$$\bigwedge_i \mu_{\tilde{P}}(x_i) \leq \tau(x_1, x_2, \dots, x_n) \leq \bigwedge_i \mu_{\tilde{G}}(x_i) \quad (5)$$

for $i = 1, \dots, n$. Notice that for all x in \tilde{P} , $\mu_{\tilde{P}}(x) \leq \mu_{\tilde{G}}(x) \leq \mu_{\tilde{G}}(x)$, and that \tilde{T} 's f -restriction to \tilde{P} is \tilde{R} , written $\tilde{T} \searrow \tilde{P} = \tilde{R}$.

We refer to the minimal f -extension whenever we consider fuzzy extensions on \tilde{R} . Relative to the definitions just outlined, the minimal f -extension of \tilde{R} on $\tilde{G} \supseteq \tilde{P}$ is the fuzzy n -ary relation \tilde{T} denoted by $\tau: \tilde{G}^n \rightarrow [0, 1]$, and given by

$$\tau(x_1, x_2, \dots, x_n) = \begin{cases} \rho(x_1, x_2, \dots, x_n), & \text{if this is} \\ & \text{defined;} \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

2.3 Definitions

Let the universe X be a non-empty finite set. X is called the reference set in some fuzzy literatures [7]. The degree of subsethood of \tilde{A} in \tilde{B} for fuzzy subsets $\tilde{A}, \tilde{B} \in [0, 1]^X$, written $\mu_{[0,1]^X} \tilde{A}$, is a measure of uncertainty in terms of the possibility, π , defined as

$$\mu_{[0,1]^X} \tilde{A} = \pi(\tilde{A} \subseteq \tilde{B}) \quad (7)$$

where $\mu_{[0,1]^X} \tilde{A}$ denotes the membership function that maps \tilde{A} to the power set of \tilde{B} . The value returned by $\mu_{[0,1]^X} \tilde{A}$ would depend on the fuzzy implication operator utilized to embody the said mapping, since by definition

$$\pi(\tilde{A} \subseteq \tilde{B}) = \min_{x \in X} (\mu_{\tilde{A}}x \rightarrow \mu_{\tilde{B}}x). \quad (8)$$

This is similar to a *horah* criterion for computing the triangle subproduct of two binary relations, given by

$$(R \triangleleft S)_{ik} = \min_j (R_{ij} \rightarrow S_{jk}) \quad (9)$$

in relations theory. This latter equation derives the degree of subsethood of the *afterset* of R with the *forest* of S for some fixed $x_i \in \text{dom}(R)$ and $x_k \in \text{ran}(S)$. A *moderate* criterion utilizes the *mean*.

We are now ready to define a fuzzy cognitive map, $\tilde{M} = (C_{\tilde{M}}, \mathcal{R}_{\tilde{M}})$ over the universe X . Zadeh's fuzzy sets theory [13] utilizes the closed interval of reals $\mathcal{R} = [0, 1]$ as a range set, although linguistic terms are also possible. Hence, a fuzzy cognitive map is a fuzzy graph [9] that is a 2-tuple of functions $\mu: C \rightarrow [0, 1]$ and $\rho: C \times C \rightarrow [0, 1]$, for $C \in [0, 1]^X$:

- $C_{\tilde{M}} \in [0, 1]^X$ is a fuzzy concept space of X . Unlike Kosko's formulations, the notions of quantity space and modifier space [8] are not considered here. These were developed in conjunction with the linguistically-inclined documentary encoding task of Axelrod.

- $\mathcal{R}_{\tilde{M}}$ is a fuzzy relation on $C_{\tilde{M}} \in [0, 1]^X$, given by $\mathcal{R}_{\tilde{M}}: C_{\tilde{M}} \times C_{\tilde{M}} \rightarrow \mathcal{R}$. The values of $\mathcal{R}_{\tilde{M}}$ are restricted by formula (3), and so

$$\mathcal{R}_{\tilde{M}ij} \leq \mu_{C_{\tilde{M}}} x_i \wedge \mu_{C_{\tilde{M}}} x_j$$

for all $x_i, x_j \in C_{\tilde{M}}$.

- The totally ordered range set $\mathcal{R} = [0, 1]$ establishes the certainty or membership values between concepts $C \in C_{\tilde{M}}$.

2.3.1 Operations

We define the following operations on arbitrary fuzzy cognitive maps $\tilde{M} = (C_{\tilde{M}}, \mathcal{R}_{\tilde{M}})$ and $\tilde{N} = (C_{\tilde{N}}, \mathcal{R}_{\tilde{N}})$ over the universe X :

- The fuzzy join of \tilde{M} and \tilde{N} is denoted by

$$\tilde{M} \oplus \tilde{N} = (C_{\tilde{M}} \cup C_{\tilde{N}}, \mathcal{R}_{\tilde{M}} \cup \mathcal{R}_{\tilde{N}}) \quad (10)$$

where \cup is the fuzzy set union operator and \cup is the fuzzy relational union operator, defined as

$$\forall x \in X, \mu_{C_{\tilde{M}} \cup C_{\tilde{N}}}(x) = \mu_{C_{\tilde{M}}}(x) \vee \mu_{C_{\tilde{N}}}(x)$$

$$\mathcal{R}_{\tilde{M}} \cup \mathcal{R}_{\tilde{N}} = (\mathcal{R}_{\tilde{M}} \cup \mathcal{R}_{\tilde{N}})_{ij} \vee (\mathcal{R}_{\tilde{N}} \cup \mathcal{R}_{\tilde{M}})_{ij}$$

respectively. The \vee symbol denotes the maximum operator.

- The fuzzy meet of \tilde{M} and \tilde{N} is denoted by

$$\tilde{M} \otimes \tilde{N} = (C_{\tilde{M}} \cap C_{\tilde{N}}, \mathcal{R}_{\tilde{M}} \cap \mathcal{R}_{\tilde{N}}) \quad (11)$$

where \cap is the fuzzy set intersection operator and \cap the fuzzy relational intersection operator, defined as

$$\forall x \in X, \mu_{C_{\tilde{M}} \cap C_{\tilde{N}}}(x) = \mu_{C_{\tilde{M}}}(x) \wedge \mu_{C_{\tilde{N}}}(x)$$

$$\mathcal{R}_{\tilde{M}} \cap \mathcal{R}_{\tilde{N}} = (\mathcal{R}_{\tilde{M}} \cap \mathcal{R}_{\tilde{N}})_{ij} \wedge (\mathcal{R}_{\tilde{N}} \cap \mathcal{R}_{\tilde{M}})_{ij}$$

respectively. The \wedge symbol denotes the minimum operator.

- The fuzzy discrepancy of \tilde{M} over \tilde{N} is denoted by

$$\tilde{M} \ominus \tilde{N} = (C_{\tilde{M}} \setminus C_{\tilde{N}}, \mathcal{R}_{\tilde{M}} \setminus \mathcal{R}_{\tilde{N}}) \quad (12)$$

where \setminus is the fuzzy set difference operator and \setminus is the fuzzy relational negation operator, defined as

$$\forall x \in X, \mu_{C_{\tilde{M}} \setminus C_{\tilde{N}}}(x) = \mu_{C_{\tilde{M}}}(x) \wedge (1 - \mu_{C_{\tilde{N}}}(x))$$

$$\mathcal{R}_{\tilde{M}} \setminus \mathcal{R}_{\tilde{N}} = (\mathcal{R}_{\tilde{M}} \setminus \mathcal{R}_{\tilde{N}})_{ij} \wedge (\mathcal{R}_{\tilde{N}} \setminus \mathcal{R}_{\tilde{M}})_{ij}$$

respectively.

The fuzzy join operation can be utilized to create and link cognitive maps. Truncation or pruning is accomplished by taking the fuzzy meet. Meanwhile, fault-detection is performed by taking the fuzzy discrepancy of the approximated chain-of-thought with a cognitive map supplied by the expert.

2.3.2 Relations

The following relations on arbitrary fuzzy cognitive maps $\tilde{M} = (C_{\tilde{M}}, \mathcal{R}_{\tilde{M}})$ and $\tilde{N} = (C_{\tilde{N}}, \mathcal{R}_{\tilde{N}})$ over the universe X are defined:

- \tilde{M} is called a fuzzy submap of \tilde{N} , written $\tilde{M} \prec \tilde{N}$, if the following hold:

$$\tilde{M} \prec \tilde{N} \Leftrightarrow \pi(C_{\tilde{M}} \subseteq C_{\tilde{N}}) \geq \alpha_C, \text{ and } (13)$$

$$\mathcal{R}_{\tilde{M}} \subseteq \mathcal{R}_{\tilde{N}} \setminus C_{\tilde{M}} \quad (14)$$

for some preset threshold α_C , usually set at $\alpha_C = 0.5$, and where

$$\pi(C_{\tilde{M}} \subseteq C_{\tilde{N}}) = \min_{x \in X} (\mu_{C_{\tilde{M}}}(x) \rightarrow \mu_{C_{\tilde{N}}}(x)) \text{ and}$$

$$\mathcal{R}_{\tilde{M}} \subseteq \mathcal{R}_{\tilde{N}} \setminus C_{\tilde{M}} \Leftrightarrow \forall i, j \quad \mathcal{R}_{\tilde{M}ij} \leq (\mathcal{R}_{\tilde{N}} \setminus C_{\tilde{M}})_{ij}$$

- \tilde{M} is called a fuzzy supermap of \tilde{N} , written $\tilde{M} \succ \tilde{N}$, if the following hold:

$$\tilde{M} \succ \tilde{N} \Leftrightarrow \pi(C_{\tilde{M}} \supseteq C_{\tilde{N}}) \geq \alpha_D, \text{ and } (15)$$

$$\mathcal{R}_{\tilde{M}} \setminus C_{\tilde{N}} \supseteq \mathcal{R}_{\tilde{N}} \quad (16)$$

for some preset threshold α_D , usually set at $\alpha_D = 0.5$, and where

$$\pi(C_{\tilde{M}} \supseteq C_{\tilde{N}}) = \min_{x \in X} (\mu_{C_{\tilde{N}}}(x) \rightarrow \mu_{C_{\tilde{M}}}(x)) \text{ and}$$

$$\mathcal{R}_{\tilde{M}} \setminus C_{\tilde{N}} \supseteq \mathcal{R}_{\tilde{N}} \Leftrightarrow \forall i, j \quad (\mathcal{R}_{\tilde{M}} \setminus C_{\tilde{N}})_{ij} \geq \mathcal{R}_{\tilde{N}ij}$$

- \tilde{M} is said to be equal to \tilde{N} , written $\tilde{M} = \tilde{N}$, when the following hold:

$$\tilde{M} = \tilde{N} \Leftrightarrow C_{\tilde{M}} = C_{\tilde{N}} \text{ and } \mathcal{R}_{\tilde{M}} = \mathcal{R}_{\tilde{N}} \quad (17)$$

which means that

$$\forall x \in X, \mu_{C_{\tilde{M}}}(x) = \mu_{C_{\tilde{N}}}(x)$$

$$\text{and } \forall i, j \quad \mathcal{R}_{\tilde{M}ij} = \mathcal{R}_{\tilde{N}ij}$$

Otherwise, \tilde{M} is not equal to \tilde{N} , written $\tilde{M} \neq \tilde{N}$.

The cognitive map relations just presented could be utilized for comparing and analyzing approximated structures with idealized ones. Fuzzy orders [14] could provide interpretations of conceptual manipulation strategies employed by a particular novice. Other useful applications are still being investigated.

3 Implementation: Some Useful Properties

Some of the relevant knowledge acquisition problems are alleviated by utilizing the concept of *clonages* from mathematical relations theory [3,4]. This allows the free-hand entry of data by connecting frame-like nodal

structures representing concepts. The system will then attempt to establish the desired relation and conceptual ordering prior to analysis.

It is conjectured here that for any cognitive map $M = (C_M, R_M)$, R_M is the transitive closure of the entered nodal connectivity, R' , supplied during the knowledge acquisition phase. This stems from the proposal that R_M is transitive. Choose to consider R' irreflexive and strictly anti-symmetric, since in adjacency matrix notation, the properties

$$\forall r \in R, R'_{ii} = 0, \quad (18)$$

$$\text{and } \min_{i,j} (R'_{ij}, R'_{ji}) = 0 \quad (19)$$

hold. The transitive closure of R' , which is the least inclusive transitive relation containing R' [4], is a strict order that is exactly R_M . This relation is computed by taking the circlet product or the max-min composition of the local preorder closure of R' with itself

$$\text{tra clo } R' = (\text{locpre clo } R') \circ R' = R_M \quad (20)$$

as suggested by a fast algorithm in [4].

4 Conclusions

We have proposed the use of fuzzy cognitive maps to represent an approximation of the concept manipulation and formation strategy employed by a novice in attempting to solve a particular problem. Corresponding fuzzy formulations are developed utilizing relations theory and the notion of restrictions and extensions. Interpretation of the resulting conceptual graph structures, which would be parallel to a conceived solution path, is derived by utilizing order relations. Furthermore, this approach's applicability to other abductive systems requiring some fault detection or error diagnosis is being considered. We are currently investigating other plausible possibilistic formulations as well. These provide sufficient initiative to continue extensive research on the subject area.

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The Coming of Age of Fuzzy Logic

James C. Bezdek, Editor

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The Coming of Age of Fuzzy Logic

Message from the Congress Chair and Proceedings Editor

The proceedings for the Third World Congress of IFSA - the *International Fuzzy Systems Association*, reflects both the breadth and depth to which fuzzy sets and their applications have pervaded nearly all realms of the mathematical, computational, physical and social sciences and related engineering disciplines. One need only glance through the session titles to appreciate the current scope and extent of the field. Rather than itemize the various disciplines that are now represented at this meeting, I invite you to browse through the program. Even a cursory glance should convince most readers that our field has reached a plateau of stability and maturity that is increasingly evident as fielded systems exhibiting real applications find their way into international markets. Concomitant developments in the theory have led to a deep and satisfying structure that tends to complement and supplement models that have other, more conventional bases.

It has been my great pleasure to work with the program committee and the IFSA council during the planning and assembly of the conference. I want to single out here for their exemplary help the four day chairs, who really did all the hard work. My sincere and heartfelt thanks, then, to: Drs. Ron Yager, Hideo Tanaka, Ulrich Hohie and Henri Prade. Dr. Edith Martin, Vice President and Director of the Boeing Aerospace and Electronics High Technology Center also deserves mention: without her patience and support (both direct and indirect), the congress would not have been held in Seattle. Finally, a special thanks to Jan Kvamme at the University of Washington, who took diligent care of the unending details of local arrangements at the campus.

Most Sincerely,

Jim Bezdek
Aug. 6, 1989

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Professor Wylie Bandler
Computer Science Department
Florida State University
Tallahassee, FL 32306, USA

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USA

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PO Box 24999 : MS 7J-24
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118 Route de Narbonne
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Langages et Systemes informatiques
Université Paul Sabatier
118 Route de Narbonne
31062 Toulouse Cedex, FRANCE

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Illinois Wesleyan University
Bloomington, Illinois
61701, USA

Prof. Toshiro Taneno
Hosei University
3-7-2 Kojino-Cho
Kojanai, Tokyo 184
JAPAN

Dr. Richard Tong
Advanced Decision Systems
201 San Antonio Circle, Suite 28
Mountain View, CA 94040
USA

Dr. Ronald Yager : Chair, Day 1
Machine Intelligence Institute
Iona College
New Rochelle, NY 10801
USA

Prof. Maria Zemanikova
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University of Tennessee
Knoxville, Tennessee 37996
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Prof. Robert Lowen
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