A THEORETICAL FRAMEWORK FOR MODELING CHAINS-OF-THOUGHT: AUTOMATING FAULT DETECTION AND ERROR DIAGNOSIS IN SCIENTIFIC PROBLEM SOLVING*

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ABSTRACT

This paper presents an on-going exploratory study concerning the cognitive processes involved during scientific problem solving. It is conceived that by ascertaining the novice's (in this case, the student user's) *chain-of-thought*, developed while solving a particular problem, a cognitive perspective aiming for a better understanding of the mental processes involved could be achieved. The approximated cognitive structure is correlated with correct or expected versions supplied by the expert (tutor or educator). Such a comparison is asserted to generate valuable information for diagnosis, direction, and eventual correction and improvement of the novice. A theoretical framework, based on a *cognitive map* implementation, is discussed. It attempts to capture the underlying cognitive mechanisms that govern successful fault detection and error diagnosis in problem solving. These formulations are surmised to be significant for possible implementation of diagnostic modules for intelligent tutoring systems that embody the proposed paradigm. We humbly emphasize that this endeavor aims to contribute to a better understanding of the functional aspects of the human mind.

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INTRODUCTION

A growing interest towards problem solving has been evolving among cognitive scientists (Good *et al.* 1986). The understanding and cultivation of successful problem solving techniques has been the primary concern of related studies. These not only involve the instruction of various methodologies and their underlying notions and mechanisms. The diagnosis and possible improvement of effectively utilized approaches are considered as well. Feedback from such diagnoses could aid in the development of more challenging or befitting problems that could be categorized for ameliorating both critical and analytical skills concerned.

In corroboration with the growing interest in cognitive studies related to education, the Florida State University's Department of Computer Science and Institute for Cognitive Sciences launched a research project centering on computerized diagnostic methods for improved instruction. The main objective was to come up with an expert system called DIPS, which stands for Diagnosis for Instruction in Problem Solving. Initially, an effort was made to apply the study in the field of physics (Good *et al.* 1986; Szabo 1987). But with the emergence of valuable data on classical genetics problem solving (Smith 1983; Smith and Good 1984) and the National Science Foundation (NSF) research project, "Computer Diagnosis of Faults in Genetics Problem Solving", a new approach was considered. Details of earlier work pertaining to DIPS can be found in (Good *et al.* 1985; Szabo 1987).

This study is somewhat related to current research (Bandler *et al.* 1988; Mancini and Bandler 1988), that develop and compare various constructs involved in cognitive processes. Other interesting approaches are suggested in various literature (Minsky 1986; Sowa 1984). Some methods for computer coaching (*e.g.* as that in *Wumpus* (Goldstein 1980)) are also available.

CHAINS-OF-THOUGHT

The importance of the *chain-of-thought* concept is made apparent within the context of an idealized *Tutor-Novice Model*. Relative to this model, an analogous system of conceptual structures could be formulated for embodying the concept in a computer. This is the current focus of this research.

Perhaps the most challenging aspect of this study is the fact that numerous problem solving systems have previously been developed, but only a few have emerged for diagnosing the problem solving task (Feigenbaum and Barr 1981; Feigenbaum and Cohen 1982; Goldstein 1980; Newell and Simon 1972). Indeed, developing a system capable of solving a specified class of problems is, in itself, a difficult undertaking. What about a program that assesses problem solving by determining how the problem solver is thinking? Or perhaps a program that approximates the concept formation and manipulation employed by a problem solver in attempting to solve a particular problem? This is exactly how a tutor goes along in directing the course of a session with a novice. A problem is presented for solving. The problem is familiar to the tutor, who associates to it a *solution map* that embodies various solutions known to him. By observing both verbal and non-verbal actions (Ericsson and Simon 1984; Gagne 1966) exhibited by the novice (*e.g.* combinations of written partial solutions, visual contact, bodily movements and others), the tutor detects any faults made by the novice. These are actually deviations from the solution map in his mind and could therefore be diagnosed to generate some appropriate advisory information. The perceived protocol is then noted, synthesized and manipulated by the tutor. The novice, on the other hand, attempts to finally solve the problem successfully based on the hints and comments provided by the tutor.

So, the chain-of-thought referred to here pertains to the line of thinking, or successive linking of concepts utilized to solve a problem. By approximating this structure, the tutor is able to effectively diagnose the problem solving skills of the novice. It is in this manner that our system develops and maintains a *model of the novice*, an important feature provided by our approach.

Cognitive Maps

We now focus our attention on the use of *cognitive maps* (Axelrod 1972; Axelrod 1976; Sowa 1984) in order to capture the essence of the approach just presented. These conceptual structures, introduced by cognitive psychologist E. C. Tolman in 1932 , could be viewed as a collection of nodes semantically linked in a fastidious manner (Hayes 1979; Minsky 1981; Quillian 1967; Schank and Abelson 1977) . Axelrod utilized these structures to represent causality in social scientific knowledge (Axelrod 1976). They facilitated documentary coding by providing symbolic representations of expert documents.

Correspondence with the Tutor-Novice Model

The scientific knowledge with which Axelrod utilized cognitive maps for representation allowed the simple utilization of the (adjacency) matrix to measure causal chaining information and for performing causal reasoning. But in order to capture the mental processes involved in problem solving, as exemplified by the Tutor-Novice Model, a different approach is used here. By taking into consideration the role of the tutor for this model, it is presumed that functionally distinct cognitive maps are maintained within the tutor's mind to successfully carry out diagnostic functions. Furthermore, the representation utilized by Axelrod is insufficient for the evolving or constructive approach outlined earlier. This would result to sparsity.

We conjecture the sufficiency of three cognitive maps. Firstly, a *Domain-Specific cognitive map* that embodies the *generic* (Sowa 1984) conceptual formulations characteristic of the field of discourse under which the problem solving task is to take place (*e.g.* physics, classical genetics, algebra). This represents the tutor's knowledge and expertise in the subject area being considered. Secondly, a *Problem-Specific cognitive map* that incorporates both generic and *referent* (Sowa 1984) concepts involved with the successful solution of a particular problem. This depicts the solution map associated to each of the individual problems presented to the novice. Lastly, the approximation of how the novice is thinking relative to the successful development of a solution to the problem is embodied in what is referred to as the *Novice's Chain-of-Thought cognitive map*.

This approach considers an *overlay* (Goldstein 1980) or *subset* relation between the tutor's expertise and the student's knowledge. This is further exhibited by the structural equivalence of the cognitive maps. The major difference lies in the information encoded within the nodes of each conceptual structure as well as the fact that the model of the student's knowledge is generated during a particular session.

The possibility of utilizing the matrix representation in conjunction with the digraph representation utilizing nodes and arcs is being considered. But current attempts of implementing the system consider only the latter scheme in some specified abstract data type.

Fuzzy Structures

When the complexity of a particular system increases, uncertainty is bound to prevail. This phenomenon applies to society, as well as specific tasks like decision-making and planning, and others. It is also true with problem solving. More complex problems have a higher degree of difficulty, thereby demanding a higher level of intelligence. Hence, when a student is faced with such problems, partial and complete solutions are usually presented with some measure of uncertainty. In such situations, classical bi-valued logic becomes insufficient, if not inappropriate, to capture the intricacies involved.

To capture such imprecision, Zadeh introduced the theory of *fuzzy sets* (Zadeh 1965) . Since then, research on *fuzzification* of formerly *crisp* systems have sprung, particularly on knowledge representation (*e.g.* fuzzy frames (Graham and Jones 1987)) and inductive methods for expert systems. Some recent studies have also shown the plausibility of incorporating causal symbolic inferences with numeric *probabilistic* inference. But we are more interested here in combining symbolic inferences with fuzzy or *possibilistic* inferences or inferences under uncertainty. This latter composition would be appropriate to more situations than the traditional probabilistic or *Bayesian* methods (Bandler and Kohout 1985; Bhatnagar and Kanal 1986) .

Now, consider the scenario when a novice presents some partial or complete solution, preceding the answer with *Maybe* or *I think*. The tutor should readily notice a lower degree of certainty associated with such responses. But how is this to be represented within the cognitive maps? It is asserted that cognitive maps could be fuzzified by introducing strength measures on relational links connecting the semantically rich conceptual nodes of a map. A corresponding *fuzzy cognitive map algebra* (Kosko 1986) could be developed to precisely define inference modalities within the structures.

In connection with the conceptual structures used in this study, only the *Novice's Chain-of-Thought* cognitive map will be fuzzified. The other two maps remain crisp since they are already established facts and are expected to be precise and exact. The measures of strength are to be assigned by some linguistic variable (Zadeh 1979) interpreter that would approximate these values. Certainly, a problem arises here — the various ways to implement such an interpreter to capture the very great variety of discriminant principles utilized by tutors (Bandler and Kohout 1980a; Bandler and Kohout 1980b) . This issue is crucial for implementing these cognitive structures, most specially for the map-matching algorithm that would generate diagnostic information based on the performance of the novice.

We point out the issue of formulating a plausible measure of the *degree of subsethood* relation between pairs of cognitive maps under consideration. Such a measure of uncertainty has been suggested (Bandler and Kohout 1980) in terms of the possibility, π, and is defined as

$$\pi(A \subseteq B) = \mu_{\mathcal{P}(B)} A$$

where $\mu_{\mathcal{P}(B)} A$ denotes the *membership function* that maps A to the *power set* of B. The value returned by $\mu_{\mathcal{P}(B)} A$ would depend on the *fuzzy implication* operator utilized to embody the said mapping.

The Tri-Map Configuration

Relative to the cognitive maps discussed earlier, this study further asserts that successful automation of fault detection and error diagnosis of problem solving skills greatly depends on some operational and relational manipulations invoked by a predetermined map-matching algorithm. Theoretically, the cognitive maps must be accessible to the algorithm to allow the performance of specific functions necessary to generate the appropriate diagnostic results. It is envisioned that, at least conceptually, some form of *Tri-Map Configuration* should be established to facilitate overlay-like comparisons between the distinct cognitive maps involved.

Fault Detection

If the cognitive maps were to be intuitively characterized as opaque nodes interlaced on a translucent plane and the algorithmic manipulations as a light source, then fault detection becomes straightforward. Passing this "light" vertically through the cognitive structures, positioned as in a Tri-Map Configuration, would detect deviations that represent faults. These *negative* or *anti*-nodes must be noted for interpretation. This suggests a correspondence with *differential* models that recognise and summarise the student's behavior (Dede 1986). Some mathematical formulations could be made for *discrepancy* operations that embody this approach, and these are currently being considered.

Alternate solutions presented by the student user are considered. We emphasize that these deviations from the methodology expected by the expert, which may actually represent better solutions, could be investigated by systems utilizing this approach via backward chaining guided by the ***Domain-Specific*** and ***Problem-Specific*** cognitive maps. This provides a more user-friendly system behavior geared towards motivation.

Error Diagnosis

Equally important to the function of fault detection is the diagnosis of the error detected. The conglomeration of negative nodes, representing deviations from the idealized paths, may be categorized for error classification. Since the nodes are semantically rich, diagnosis is performed by extracting the required information from the nodes concerned. It is pointed out that the tutoring capability of the system is derived from this information. The problem of credit/blame appointment is also resolved, specially with the fuzzified approach, similarly with the so-called *perturbation* models (Dede 1986). This also suggests an effective pedagogical mechanism for the system that could hopefully induce learning within the subject domain concerned.

AN OPEN INVITATION

What useful information could be generated by implementing such an approach? Firstly, from a psychological viewpoint, it is presumed that a better understanding of a specific class of mental processes could be achieved (Greeno 1980; Minsky 1986; Newell and Simon 1972; Schoenfeld 1984). This should prove to be helpful for the unending quest to gain a deeper understanding of the human mind and its intricacies. Secondly, from the educator's viewpoint, it could provide information regarding measures of strengths of currently existing curricula (Reif 1980; Simon 1980). This could also indicate certain flaws in the method of instruction being utilized. Last, but not the least, we cannot overlook its inherent tutoring capability. This is important for improving an individual's problem solving skills.

We have remained silent in suggesting other areas where this framework could be applied. Surely, pattern recognition, fault detection and error diagnosis are areas of interest. We have also been considering abductive systems, as well as other plausible possibilistic formulations for the fuzzy case. Such conceptions necessitate further investigation of methods for integrating symbolic causal inference with fuzzy inference in the context of the Tri-Map configuration discussed in this study. All these, and perhaps more, provide an open invitation for future research.

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Welcome to the (mirabile dictu!) SECOND meeting of FLAIRS! In the wake of last year's large and very enthusiastic turnout, we had considered renting a larger facility -- Iceland, for example -- but concluded eventually that the Holiday Inn in Orlando would continue to do nicely. We couldn't, in any case, figure out how to say, "The Neural Nets tutorial is in Ballroom B," in Icelandic.

For those of you attending for the first time, FLAIRS was organized last year by a group of AI researchers and professionals in academe and in industry, with the intent of establishing a permanent network of activity for the Florida AI community. The overwhelming success of last year's symposium attests to the considerable vitality of that community, and we hope this year to stimulate an even higher level of interest.

The theme of FLAIRS-89 is knowledge engineering, and in addition to a broad diversity of high-quality papers reflecting that focus, we are especially pleased this year to boast four speakers who are nationally known AI experts, and a full roster of tutorials on the various AI sub-disciplines. We are pleased also to be able to offer a full exhibit hall, and hasten to proclaim our appreciation to the very supportive exhibitors listed on the next page.

Thanks, finally, to our tireless Organizing Committee - the people who multitasked valiantly against the onslaught of time, the non-onslaught of money, and the generalized encroachments of entropy in all of its guises. And special thanks to you, the authors and attendees, whose participation has been the essential element to help make Florida an even more important AI center.

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