A Formal Model for Metacognitive Reasoning in Intelligent Systems

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ABSTRACT

This paper presents a formal model of metacognitive reasoning in intelligent systems (IS). The proposed model was named fM² and uses predicate logic to represent a cycle of reasoning about failures generated in reasoning tasks in an IS. fM² has mechanisms such as introspective monitoring and meta-level control to perform metacognitive reasoning. fM² was implemented and validated on an intelligent tutoring system named FUNPRO. The performance metrics of FUNPRO indicate the capacity of fM² to drastically decrease the reasoning failures produced in the recommendations of FUNPRO. Thus, this paper demonstrates the efficacy of fM² as a valid tool to improve the performance of the reasoning processes of IS.

Keywords: Artificial Intelligence, Cognitive Reasoning, Intelligent Tutoring System, Meta-Level Control, Metacognitive Reasoning

1. INTRODUCTION

Cognitive Informatics is a multidisciplinary research area that investigates the internal information processing mechanisms of the brain and natural intelligence shared by almost all science and engineering disciplines (Wang, 2007). Cognitive Computing is an emerging paradigm of Artificial Intelligence (AI) based on Cognitive Informatics, that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain and natural intelligence (Wang et al., 2010).

Metacognition in Cognitive Computing refers to the capability of Intelligent Systems (IS) to monitor and control their own learning and reasoning processes. Reasoning and learning processes are two higher level cognitive functions of natural intelligence. Metacognition allows IS to gain awareness of knowledge about cognition and control of cognition.

Now a days increasingly complex IS that make decisions based on multiple variables are being developed. The complexity increases the

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probability that reasoning failures occur in an IS (Conitzer & Sandholm, 2003; Cox, 2005; Schmid, Ragni, Gonzalez, & Funke, 2011). A reasoning failure is defined as an outcome other than what is expected or a lack of some outcome or appropriate expectation (Cox, 1997). Reasoning failures are generated mainly by unfinished tasks or unexpected results in the performance of a task. Metacognition provides introspective monitoring and meta-level control mechanisms for an IS to detect and correct its own reasoning failures.

Diverse formal models of the brain and mind have been developed in the field of Cognitive Informatics. The layered reference model of the brain (LRMB) (Wang, Wang, Patel, & Patel, 2006) presents a formal and rigorous explanation of the functional mechanisms and cognitive processes of natural intelligence. In LRMB, metacognitive processes are formally described and are arranged in an upper layer of the model. However, the model does not explicitly describe the inherent mechanisms to solve reasoning failures using metacognitive control. Wang describes in (Wang, 2008) formal models for a set of metacognitive processes of the brain using two denotational mathematics, real-time process algebra (RTPA) and concept algebra. Although the metacognitive processes are rigorously formalized, in this work the mechanisms of introspective monitoring and meta-level control applied to the solution of reasoning failures are not described.

Moreover, several models of metacognition focused on solving reasoning failures have been described in the literature. In (Cox, 1997) a formal representation of reasoning failures is presented, but without formally describing the meta-reasoning rules that allow the system to respond to reasoning failures.

Other studies describe different approaches to modeling reasoning failures in intelligent systems. Some works such as (Josyula et al., 2010; Schmill et al., 2007) present models based on ontologies. Case-based Reasoning has been used by (Mehta & Onta, 2009; Soh & Blank, 2008) to represent metacognitive models that respond to reasoning failures. However, none of the models described has approached the description of processes associated with the metacognitive reasoning from a formal perspective. More recent works as (Erdem, Aker, & Patoglu, 2012) describe formalisms for robots responding to failures. However the robot is not able to solve the failure itself but rather seeks help from other robots.

In the context described, the main objective of this paper is to introduce a formal Metacognitive Model for monitoring and control of reasoning failures in intelligent systems. The proposed model is named $fM^2$ and has support for introspective monitoring and meta-level control. $fM^2$ uses predicate logic to represent the basic rules of metacognitive reasoning. $fM^2$ was implemented in an Intelligent Tutorial System (ITS) using SWI-Prolog. The results of validation test indicate that the implementation of $fM^2$ was able to reduce the number of failures of reasoning in IS.

The paper is structured as follows. In Section 2, we describe the proposed metacognitive model. Section 3 presents the implementation of $fM^2$ in an ITS. Section 4 describes the evaluation process and presents performance metrics to validate the model. Finally, we present the discussion and conclusions.

### 2. FORMAL MODEL FOR IS METACOGNITION

$fM^2$ is a Metacognitive Model for monitoring and control of reasoning failures in intelligent systems (IS). $fM^2$ consists of a cycle of reasoning about failures generated in the reasoning task in an IS, see Figure 1. The reasoning cycle inputs are the computational data generated in reasoning task and the output consists of recommendations which may vary according to the reasoning task. In particular, we will focus on the reasoning process that allows choosing the best strategy to correct the reasoning failure.

To describe $fM^2$ in detail, first in section A, the main elements that comprise the model are described. Then in Section B, the object-level specification is presented. In Section C,
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