A Framework to Induce Self-Regulation Through a Metacognitive Tutor

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Abstract

A new architectural framework for a metacognitive tutoring system is presented that is aimed to stimulate self-regulatory behavior in the learner. The new framework extends the cognitive architecture of TutorJ that has been already proposed by some of the authors. TutorJ relies mainly on dialogic interaction with the user, and makes use of a statistical dialogue planner implemented through a Partially Observable Markov Decision Process (POMDP). A suitable two-level structure has been designed for the statistical reasoner to cope with measuring and stimulating metacognitive skills in the user. Suitable actions have been designed to this purpose starting from the analysis of the main questionnaires proposed in the literature. Our reasoner has been designed to model the relation between each item in a questionnaire and the related metacognitive skill, so the proper action can be selected by the tutoring agent. The complete framework is detailed, the reasoner structure is discussed, and a simple application scenario is presented.

Introduction

Recently, scientific literature related to Intelligent Tutoring Systems (ITS) has registered a growing interest in the adoption of cognitive and meta-cognitive strategies while guiding the interaction with the system to make the learning process more effective. Such strategies are useful to promote the comprehension and retention of new knowledge by the user. Moreover, the main goal is to induce metacognition in the learner itself that is the capability of thinking about and managing her cognitive state with respect to the learning task.

The purpose of this work is to introduce an extension towards metacognition in TutorJ, a cognitive and modular framework for ITSs already presented by some of the authors (Pirrone, Rizzo, and Pilato 2008) (Cannella and Pirrone 2009). TutorJ is an architectural framework for ITSs that is already able to support a student during a learning session by supplying learning material customized to her cognitive needs, skills, and goals. A prototype architecture has been realized in the Arts domain to be used by graduate and/or Ph.D. students (Russo, Pipitone, and Pirrone 2009). The framework allows building a generic intelligent agent able to interact also with external information sources. The reference cognitive architecture is the Human Information Processor Model (HIPM) so the agent consists of several modules that can be classified as perceptual, cognitive and sensor-motor ones. Each module of the agent is devoted to a specific function involved in the cognitive processes. The most important tasks are: user interaction; dialogue planning; management of learning contents; building customized learning paths for the user; acquisition of new knowledge. User interaction is performed via a suitably modified chatbot that uses a mixed strategy involving both visual and natural language dialogue. Dialogue planning is achieved using different strategies that are related to the agent's goals. We devise either immediate goals per single dialogue move or final goals for the overall dialogue. The agent's behaviors are planned adaptively according to its goals, its beliefs on the user cognitive state, and its perceptions from the conversation flow. Both a deterministic (Prolog-based) and a statistical (Markov process) planning engine have been implemented to manage this very complex task. In this respect, the agent's actions are to be intended as a wide range of communication acts: text statements, graphics and documents visualization, and so on. All of these actions are aimed to cope with the cognitive processes mentioned above that is they are designed to assess, monitor, and increase the learner's knowledge.

This work presents the new architectural framework for a metacognitive version of TutorJ that is intended to stimulate self-regulatory behavior in the learner. We adopted the Self-Regulated Learning (SRL) theoretical perspective to define a new set of agent's behaviors. The main characteristics of self-regulated students are: the ability to perform cognitive strategies to address the information size growth problem; the ability to adopt time and effort strategies to optimize learning results; the exhibition of intense curiosity and motivation for novelties; the ability to perform metacognitive control processes. When managing a conversation with a student, the agent has to plan a dialogue that is not only guided by the list of topics to be deepened or by the requests issued by the user about the learning domain. The conversation has to address the self-regulated behaviors of the student to devise a set of measurements of her metacognitive skills, and to build a model of her metacognitive state.

In turn, this model is a key for a better comprehension her knowledge (i.e. cognitive) state. To face this problem, we have enriched the structure of the dialogue manager in TutorJ.

Our architecture makes use of a statistical dialogue planner implemented through a Partially Observable Markov Decision Process (POMDP). A suitable two-level structure has been designed for the statistical reasoner to cope with both "cognitive actions" and "metacognitive actions". Cognitive actions are the standard set of actions in the previous version of the system that is assessment, learning path planning, visualization of learning material, question answering, and so on. Metacognitive actions are a suitable set of communication acts aimed both to evaluate self regulated skills in the learner and to stimulate her to reflect on her metacognitive state in order to pursue a self-regulated learning. To this aim, a two-stage model of he reasoner has been devised that relies on a couple of POMDPs: the "cognitive POMDP" and the "metacognitive POMDP". Here the second POMDP has its own perceptions both from the external world (the dialogue flow) and from the actions issued by the cognitive POMDP. Such actions convey information about what is the cognitive state of the user. Moreover a suitable set of metacognitive states and actions have been defined. To this aim, we investigated the different methods proposed in the literature for measuring self-regulated skills. In our framework, the metacognitive POMDP is designed to model the relationships between such skills (state nodes) and the questionnaire items (action nodes). Finally, the two POMDPs have been suitably integrated in a unique network to better fit with the previous architectural constraints.

The rest of the paper is arranged as follows. In the next section a brief state of the art is presented about measuring metacognitive skills in SRL, and the definition of the POMDP model. In the following two sections our framework is detailed from an architectural point of view, the POMDP design is described, and a simple application scenario is presented. Finally, conclusions and future work are reported.

State of the Art

As already mentioned, our framework is oriented to stimulate the user to became a self-regulated learner. Self-Regulated learners (Zimmermann 2001) (Montalvo and Gonzales-Torres 2004) are able to deal with the information size growth problem, to adopt time and effort strategies to maximize results, and to perform meta-cognitive processes. According to Pintrich (Pintrich 2000), such students are able to perform metacognitive and regulation strategies in addiction to cognitive ones. In this work we want to obtain a computational model for self-regulated processes. One of the major issues in this respect, is to obtain a measure of the level of self-regulation during the interaction with the student. The difficulty to define a measure is a common problem for domains where uncertainty has a major role. A common way to obtain a measure of the "SRL level" in a student is to administer a questionnaire with the purpose to obtain the measure.

The more used tests over the years are the Self-Regulated Learning Interview Schedule (SRLIS) (Zimmerman and Pons 1986), the Motivated Strategies for Learning Questionnaire (MSLQ) (Paul R Pintrich and McKeachie 1993), the Metacognitive Awareness Inventory (MAI) (Schraw and Dennison 1994) and the Learning and Study Strategies Inventory (LASSI) (S. L. Nist and Kroc 1990).

The SRLIS was initially developed involving tenth grade students from both high and low achievement tracks of a suburban high school. The main purposes was to measure self-regulated learning strategies in order to determine the degree of correlation between reported use of self-regulated learning strategies and students' achievement track.

The MSLQ test is a self-report instrument designed to measure students' motivation and self-regulated learning in classroom contexts. The MSLQ is made up of two sections: the latter one. The motivation section, consists of 31 items useful to assess students' goals, their beliefs about their skill to succeed, and their anxiety. The former section, the learning strategy one, includes 31 items regarding students' use of their cognitive and metacognitive strategies.

The MAI test is a 52-item self-report instrument to measure adults' self-understanding or awareness of their metacognitive processes. There are two main categories of items addressing respectively knowledge of cognition and regulation of cognition. Jr. MAI (Sperling et al. 2002) was developed by Sperling for younger learners from the previous MAI. There are two versions of Jr. MAI. The version A included 12 items using a three-point-scale (never, sometimes, always) for use with learners in grades 3 through 5. The version B of the Jr. MAI, for use with learners in grades 6 through 9, included the same 12 items and 6 additional items. Regardless the particular testing method, SRL level is defined by a set of measures that are applied to non-physical entities so its evaluation is inherently uncertain. Moreover, our agent has to perceive SRL level using such measures, then it has to figure out the overall metacognitive state of the user that cannot be accessed directly. Finally, it has to act properly to increase the SRL level. A computational model that fits well to he problem just described is the Partially Observable Markov Decision Process (POMDP).

A POMDP is defined as a tuple $\{S, A, O, T, R, Z\}$ where:

- S represents a finite set of states that are not directly accessible so the process owns a set of beliefs $\{b(s)\}$
- A represents a finite set of actions
- O represents a set of observations
- $T : S \times A \times S \Rightarrow \Pi(S)$ is the state transition function where $T(s^{'} \mid s, a)$ is the conditional probability of passing state $s^{'}$ when the action a has been executed in the state s.
- $R : S \times A \Rightarrow R$ is the reward function and $R(s, a)$ is the expected reward for taking an action a when the agent is in the state s.
- $Z : O \times S \times A \Rightarrow \Pi(S)$ is the observing function and $Z(o \mid s, a)$ is the conditional probability function of observing o when the agent is in the state s after performing the action a.

The POMDP evolves through repeated perception-state-action cycles that are controlled by the values of the Z and T conditional probabilities and by the R function. Being in the state s, the process selects the action a that maximizes the value of R, and moves from s to $s^{'}$ with probability $T(s^{'} \mid s, a)$. Then it observes o with probability $Z(o \mid s, a)$ and updates its belief $b(s^{'})$ on the arrival state.

This model has two advantages, as we'll explain later in detail. The first advantage is merely an architectural one that is we already use a POMDP as a planner to guide the dialogue at the cognitive level. Moreover, even if two POMDPs are required in principle to model cognitive and metacognitive processes of the user, we can arrange them in a single network with two kinds of state nodes while keeping together actions and observations in their respective layers. In fact, there can be both actions and observations that can be used both in the cognitive POMDP and in the metacognitive one.

The Proposed Framework

The new framework presented in this work is inspired to a modular organization of the architecture as in the previous version. The cognitive architecture of TutorJ had a specific module devoted to the management of the cognitive aspects of its behavior. This module implemented a POMDP where the perception nodes define what the system is able to perceive from the outer environment. Action node ones defines how the system can influence the environment, while state nodes describe an internal representation of the state of the environment. In our case, the environment was represented by student's utterances, while the actions were aimed to assess her level of training, and produce a consequent training plan. Finally, the cognitive state of the student must be evaluated. In our case the cognitive state can be assumed to be what the student knows about the domain. In what follows the conceptual architecture and the actual design of the new module are reported.

The Metacognitive POMDP

The new structure of the dialogue manager is made by two POMDP layers: the "cognitive POMDP" that has been described so far, and the "metacognitive POMDP" that is laid upon the previous one. Figure 1 shows the conceptual design of this architecture.

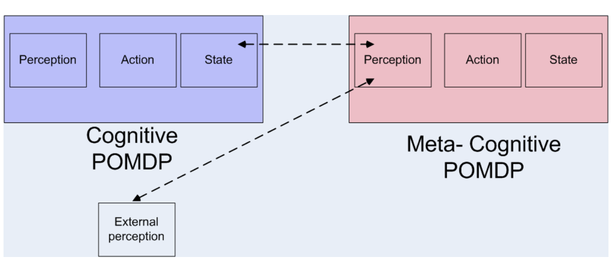

Figure 1: The cognitive and the metacognitive POMDPs

The metacognitive POMDP owns perception nodes, state nodes, and action nodes. The state of the module reflects the metacognitive state of the student. This state can not be perceived directly through the observation. In this case, observation can be obtained by administering a suitable questionnaire to assess the metacognitive state of the student and/or using emotional cues extracted by looking at the student's face and posture through a video camera. Besides direct observation of the environment, the cognitive state of the student can be a useful source of information for estimating metacognition. As a consequence some perception nodes of the metacognitive POMDP are connected to the environments, while the others linked to the outputs of the cognitive POMDP. The output nodes of a POMDP specify the actions the system has to do to obtain a certain state. The cognitive POMDP has been modified, including new action nodes, devoted to pass new perceptual stimuli to the metacognitive POMDP. As an example, it is necessary to observe the learning path size to devise if the student is anxious about the difficulty of the topic she has to learn.

The organization of state nodes in the metacognitive POMDP reflects the general structure of the questionnaires proposed in the scientific literature aiming at assessing the metacognitive aspects of a student. A reply to each question can be viewed as perception from the environment. They can shed light on some aspects of the metacognitive state of the student. These aspects can be more general facets of this state. We can distinguish many possible levels: the level of the items related to the questions, the sub-components level, and, sometimes, the categories level. As just said, the MAI questionnaire has, for instance, 52 items, grouped into 8 sub-components, which in turn are grouped into 2 categories. The state nodes in the metacognitive POMDP refer to these elements. A node can be assigned to an item, a sub-component, or a category. The arcs between them reflect their hierarchy. Starting from the general graph structure of the state nodes, we can obtain the desired topology setting to 0 the transition probabilities of unwanted arcs.

Finally, the actions of the POMDP aim at modifying the environment state, i.e. the SRL level of the student. The actual set of actions depends on the design of the state nodes that is on the choice of a particular questionnaire. Some examples of actions can be communication acts oriented to encurage the student, to reduce her anxiety, to control the time she spent for a particular topic, and so on. In general, such actions will be oriented to increase the student's awareness. These actions modify modify at the same time both the internal state of the student, and its representation in the POMDP.

Actual POMDP design

The previous description is a mere conceptualization used to make exposition simple. As a matter of fact, the new framework has still a unique POMDP module. Changes have been made in the structure of the POMDP, to allow for inclusion of both the cognitive and the metacognitive level. The module that manages the POMDP has not been modified. In this model, the cognitive nodes are directly linked to the metacognitive nodes. In this way the influence of the cognitive level on the metacognitive one is not mediated by an intermediate interaction between two distinct POMDPs. The two solutions seem different from a structural point of view, but they are analogous from a mathematical point of view. The figure 2 shows the POMDP. Blue nodes are cognitive ones; red nodes are metacognitive ones.

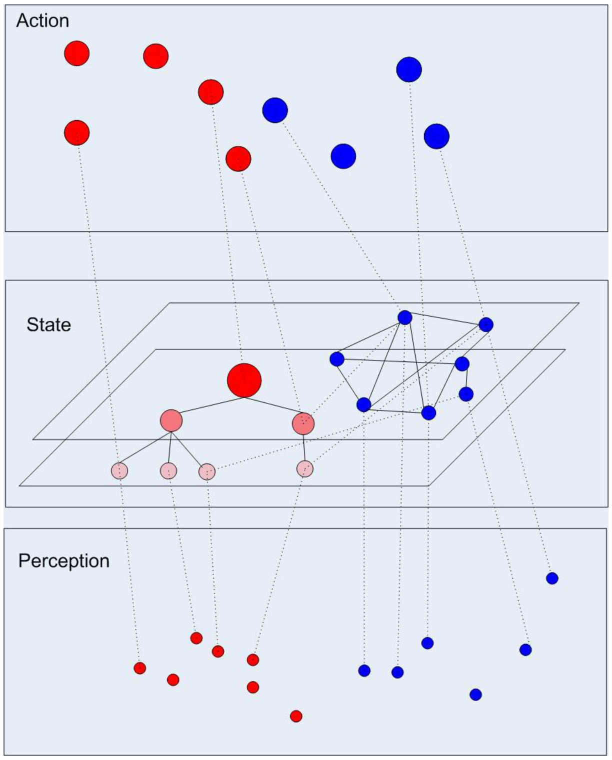

Figure 2: The integrated POMDP network

As already mentioned, the nodes of a POMDP can be connected according to whatever topology. As a consequence we merged the previous POMDPs in a unique structure where cognitive and metacognitive nodes are all together. In fact, they share the same mathematical nature even if they have different semantic and functional roles.

Nodes are mixed in all the three layers (perceptual one, state one, and action one). In the state layer, we can distinguish two distinct sub-structures. The first one is a graph made up of cognitive nodes whose interconnection reflect the relationships between the items in the learning domain according to the Knowledge Space Theory (KST) as already described in the previous version of TutorJ (Pirrone, Rizzo, and Pilato 2008). The latter one is a tree made up of the metacognitive nodes that are grouped into different levels according to the questionnaire structure.

Application Scenario

The framework described in the previous section is general. It can be adopted starting from any of the questionnaires proposed in the literature. Usually, they share a common structure. The structure of the POMDP presented in the previous section reflects the organization of questionnaires. The choice of the questionnaire should be made together with an expert. Most of the times the expert prefers to use a reduced version of a commonly used questionnaire. He/She selects a sub-set of the questions, focusing the analysis on some particular aspects of the metacognitive state of the student. This is a very common practice. There are many possible motivations for such an approach. First of all, not all the items investigated with a questionnaire are always considered useful by the expert. Some items are often omitted. This approach is further more preferred in a web interaction with the student. The interaction with the computer is usually considered more boring than interaction between humans, especially if the user does not gain immediately her goal. A questionnaire includes commonly tenths of questions. Filling such a test is considered usually a too boring task, and it can be soon abandoned. For this reason, the size of these questionnaires has to be reduced. Moreover, they can not be administered all at once. The questions have to be made in the course of the conversation, mingled with other possible other topics, or with sentences aiming at explaining their importance and meaning.

In our implementation we worked with a reduced version of MSLQ. This choice has been supported by the spread of this questionnaire, and the general approval gained by it. Moreover, it can be easily found. This choice does not exclude the use of other possible questionnaires as the basis for the definition of the POMDP.

The choice of the questionnaire induces the definition of the structure of the consequent POMDP. The values of a priori probabilities used to initialize the POMDP can be gained experimentally, or obtained by the specialized literature. The values depend on the students generic features. During the interaction the real state of the student is evaluated and modeled. The obtained POMDP is used in the subsequent interactions between the system and the student. The interaction with the student starts after she logged in. If the student has previously interacted with the system, there is a customized instance of the POMDP, which was trained with the informations gained in the previous interactions. On the contrary, a default POMDP is loaded.

In a typical application scenario, the student starts making a specific question to the system. In the first phase of the interaction, the behavior of the system is guided by the cognitive nodes of the POMDP. The system needs to know what the student wants to know, what the student knows, and what she needs to know to receive a suitable reply to her question. The result of this first phase of the interaction is the production of a possible learning path. The system has not considered metacognitive aspects till now.

After having found the list of topics related to the subject asked by the student, the system has to assess how much the student is interested in these topics or if she is frightened. Moreover, the system has to help the student to manage her learning considering her resources (learning materials, time, and so on). For instance, the system can ask how much time the student has to study the learning material, and how she wants to distribute this time for the many different topics of the learning path.

The awareness of having a too short time slot to study can induce the student to select only a part of the topics proposed in the learning path, perhaps with the help of the system. To reach such a goal, the system has to estimate the time needed to study many possible learning paths, and compared the estimated values with the available time. The estimation can be influenced by the level of interest for the specific topic, or by the complexity of the related learning material. If the estimated time exceeds, the system can offer a reduced version of the learning path. It can supply a summarized reply to the question, listing all the possible topics that could be subsequently deepened by the student. In this respect, the system can create a suitable summary through a search for the particular subject in Wikipedia. Then a page or even a single paragraph is produced that is linked to the existing material.

In a Wikipedia page, sections are indexed in a specific table, the Table of Contents (TOC) that is a tree whose the root corresponds to the category of the page and nodes correspond to the sections in the page itself. The nesting of nodes is the nesting of the sections. Using this content structure, the approach in our system consists of two steps:

- extraction of the semantic meaning of the Wikipedia sections;
- extraction of the semantic meaning of the text in a single Wikipedia section.

During first step the TOC in a Wikipedia page is extracted by a crawler and then it's transformed in an OWL fragment to be mapped in the domain ontology. Mapping is performed using the Framework For Ontology Alignment and Mapping (Ehrig 2005) and it extracts relevant concepts that correspond to the page's sections. So the system knows which concepts of the domain ontology are dealt in the page and the semantic sense of each section has been inferred. In the ontology, each relationship owns some properties describing the role of the relation name as a part of speech in a sentence dealing with the concept itself. The Penn Treebank notation is used to describe such patterns.

In the second step the system infers the semantic sense of each section by processing plain text using a POS tagger. Then all the patterns are searched that are related to the properties connected to each relevant concept. In this way a semantic wiki page is produced that is annotated with the topics requested by the user and linked with the related material in the repository.

Conclusions and Future Work

A novel framework for a tutoring system aimed to stimulate self regulation in the learner has been presented. The framework is an extension of TutorJ with the ability to estimate the metacognitive state of the student, and to put in action suitable dialogic strategies to increase the self regulation skills in the learner. The key idea is the use of standard questionnaires to measure the SRL level of the student. This is not a directly observable entity so we used a POMDP to plan the what called "metacognitive actions". The existing cognitive POMDP in TutorJ and the metacognitive one have been merged in a unique Markov process without changes in the overall architecture of the system. Some trials have been conducted with the MSLQ-based implementation of the system but no extensive experimentation is at disposal, till now. We plan to test extensively the framework jointly with some experts from Education Psychology. The main aim of this activity will be to prove the generality of the framework by verifying its effectiveness when changing the questionnaire and the particular skills to be measured.

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