A Proposal for a New Framework of Learner Modeling: From Modeling “Understanding” to “Not Understanding”

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Abstract In the study of intelligent tutoring systems (ITSs), research on learner modeling has been actively conducted to provide effective support adapted to a learner’s state of understanding, in which learning history, learning style, lack of knowledge, misunderstandings (bugs), etc. have been discussed. On the other hand, low-performance learners who genuinely need assistance find themselves in trouble because they do not know what to do, that is, they are in a state of “not understanding.” As far as the author knows, however, there is no research on modeling the state of “not understanding.” In this study, we propose a new methodology of modeling the state of “not understanding” of a learner directly based on the state space and search model used in the General Problem Solver (GPS) in AI. Then, we develop a theory for generating feedback that adequately supports low-performance learners, which can be justified by the theory of the proposed learner model.

Keywords: learner modeling, not understanding, GPS, search space, feedback generation

1. Introduction

In the research on ITSs, feedback generation, problem selection, hint generation, etc. are adaptively performed based on learner models[1,2]. Therefore, the learner model has assumed an important place in ITS research. As a result, research has been conducted on many factors, such as a learner’s preliminary knowledge, learning style, state of understanding, motivation, and degree of concentration[2]. In fact, the model of “understanding” has become focused[2,3], since one of the goals of education is to facilitate learners’ deep understanding of the subject matter. Specifically, emphasis has been placed on lack of knowledge, misunderstanding, and the use of knowledge. From a theoretical point of view, the focus has been placed on the subject of defining what constitutes “understanding.” Such a tendency is very natural, considering that it is an attractive research topic to reveal what comprises “understanding.” Interest in the state of “understanding” leads to the sense of an “Aha” moment when solving a difficult problem or when a new insight has popped up; because it is also related to a learner’s thought process at the time of invention, the scientific interest in “understanding” is unlimited. On the other hand, one of the main reasons that learners experience difficulties while learning is that they have no idea what to think or do, that is, they are in a state of “not understanding.” Nevertheless, in ITS research, there is no research that deals with and models this state of “not understanding” seriously. Considering that learners who urgently need effective support tend to be low-performance learners who cannot follow along with the rest of the class, what is needed for helping such learners is the construction of a model of “not understanding” in addition to that of “understanding.” The purpose of this short note is to propose (i) a new framework of domain-independent modeling of the state of “not understanding” based on the state space and search model used in the General Problem Solver (GPS) in AI and (ii) a system of feedback generation based on it.

This short note is concerned only with the main idea of the new type of learner modeling because the research is in the initial stage. It is organized as follows. The next section discusses the main idea of the modeling of the state of “not understanding” in a learner. Section 3 presents a rough procedure for model-building and feedback generation. Section 4 includes a discussion of the generality of the proposed method along with short related works and is followed by conclusions.

2. Modeling of the State of “Not Understanding”

States of “not understanding” seem to require modeling corresponding to two types of knowledge: procedural knowledge and declarative knowledge. We first discuss “not understanding” in problem-solving related to procedural knowledge. After that, we discuss how this concept can be extended to “not understanding”
related to declarative knowledge.

2.1 The Case of Procedural Knowledge

2.1.1 The GPS in AI

The GPS (General Problem Solver) in AI functions on the premise that every effort at problem-solving can be replaced by a search within state space. In fact, all the inferences made by implemented AI systems can be interpreted as being based on this idea. Essentially, symbolic inference is a search within a search space. In other words, human logical thinking processes can often be replaced by searches within state spaces. A state space in the GPS is modeled as a graph structure using nodes representing states and links representing state-transition relations, and actual state transitions corresponding to thinking (searching) are realized through the application of an operator. Therefore, the GPS search space and state transition can be expressed as a set of state descriptors, their possible values, and the applicable operators that represent the possible state transitions in the problem. The use of the GPS model described above is usually formulated as problem-solving, which is formulated as finding a path from the initial state to the final (goal) state and questioning the efficiency of the operator’s application strategy. A state of “not understanding” in the ordinary sense often refers to not knowing which operator is optimal for the current state. However, we do not deal with such a “knowledge operation” problem of operator application but with the existence of the search space itself. In other words, we believe that the state in which learners do not know what to do (being at a loss) corresponds to the missing state of the search space itself.

Regarding modeling a state of “not understanding,” we will examine the theory and its application, which emphasizes engineering usefulness rather than psychological validity. That is, we adopt a model in which any attempt at problem-solving is a search within the state space. However, although psychological support for the validity of the model itself is not taken into consideration, the entire framework of the state space and searches within it is consistent with psychological findings, since the SOAR model, which was developed by extending the GPS, is a cognitively valid model devised by cognitive scientists such as Newell, Laird, and Rosenbloom.

The model of “not understanding” is summarized in comparison with conventional methods in Table 1. Conventional learner modeling methods deal explicitly with knowledge and its applications to problem-solving. While they implicitly assume the existence of a search space within which learners perform problem-solving activities, our method explicitly deals with the search space itself for helping low-performance learners who are often at a loss and need effective help to get themselves out of such a state. Helping learners establish a search space contributes to an approach of suggesting what to do next rather than focusing on what knowledge is missing when solving a given problem. Guiding such students to a correct understanding of knowledge in the subject area works well for mainly middle-/high-performance learners. Although conventional methods require domain dependent knowledge, our method only requires a couple of perspectives to span the search space; hence, it is highly domain-independent. This feature enables our method to be applied to many domains to help low-performance learners more effectively than conventional methods.

2.1.2 A general Search Space

More general searches than ones within GPS search spaces can be modeled as movements in n-dimensional space in which problem-solving is modeled as finding the n-features (dimensions) that characterize a given problem to locate the optimal solution within that space and to find a path from the current (initial) state to the solution state. The state of “not understanding” can be modeled as the inability to configure such n-dimensional search spaces.

| Table 1. Summary of the Proposed Method. |
|-----------------------------------------|
| Modeling method | Target | Domain-dependence | Utility | Level of the learner |
|-----------------|--------|-------------------|---------|---------------------|
| Understanding   | Knowledge and its application | High | Guiding towards understanding | Middle/High performance |
| Not understanding | The search space | Low | Helping learners at a loss | Low performance |
A GPS-like search space is a special form of this general search space. The state corresponds to the position within the general search space, the operator corresponds to the method of movement within the space, and the types of operators correspond to the dimensions of the search space. For example, imagine completing a woodworking task. There could be many operators such as “to paint red,” “to raise,” “to scrape,” “to weigh,” “to move to the right,” etc. They would be classified as, for example, color change, shape change, weight change, and location change, which suggests that there is a four-dimensional space spanned by four features (attributes): color, shape, weight, and location. Thus, an n-dimensional search space is very general and can accommodate states of “not understanding” in relation to many problems.

2.1.3 Examples

Let us next present examples to explain how the proposed learner modeling would work. Both of the following research results have been already found using conventional ideas of learner modeling rather than our modeling. The main message we convey here is how our idea can improve the explanation of why the behavior of the existing system is effective. The argument is made for two cases.

(1) The first issue: The existence of the search space itself

Reflection on the state of a lack of a search space suggests that it can be further divided into two cases. One is the case in which the dimensions of the search space are more or less familiar to learners and others otherwise. In the first case, learners can configure the search space if the dimensions (attributes or features) are suggested by the system. In the second case, learners simply have no idea of the search space. In the latter case, it is still hard for learners to configure a search space even if the dimensions are suggested to them. The latter case is a more serious state of “not understanding” because the learners must work to make sense of the suggested attributes or features. Here is an example.

Let us take up Hirashima et al.’s triangular block model to word problems\(^{(7,8)}\) as an example. Word problems require an understanding of sentences. Conventionally, meaning representation in the mind is left implicit when people read and understand sentences. In order to cope with this issue, the researchers devised a model to express the meaning comprehension results of mathematical word problems. Although the system worked very well, the mechanism behind why it worked well was not articulated explicitly. The following is our explanation of the process.

We must note here that learners are required to have a space in which the results of understanding are represented, and the representation must be manipulable to make it possible to generate formulae. It is almost impossible for learners to configure a reasonable search space without help. The problem here is two-fold. One factor is that learners have no idea of the dimensions for such a space, and the other is that the search space spanned by the dimensions is too wide/vague. The triangular block model defines the search space itself with constraints, which effectively introduces dimensions as manipulatable triangular blocks.

(2) The second issue: The feasibility of the search within the space

It is important to distinguish between the search space within which a thought process takes place and exploration (the thought process) within the space. The most serious state of “not understanding” can be associated with a state in which the space itself does not exist (cannot be configured) in the learner’s mind. In that sense, the search “space” can be said to be the most fundamental issue. However, exploration within the search space is also extremely important, considering that the essence of thought is a process. Although a search space and exploration within it may be closely intertwined within an entity, the distinction between the two is also of essential importance.

Let us examine Hirashima et al.’s triangular block model again.\(^{(7,8)}\) One of their goals was to help low-performance learners who could not translate the key sentences in the word problem into mathematical formulae. To achieve the goal, learners need effective support when building a search space within which they can proceed to composing formulae. Therefore, the triangular model can be interpreted not only as constituting a search space but also as making objects within the space manipulatable. It is important to understand that, in their system, operations on the objects correspond to exploration of the search space. In that sense, if the search is too vague or wide, it becomes almost random, and thus infeasible. Therefore, it is also important to introduce constraints to make a search feasible. In fact, each triangular block proposed in their system contributed to introducing efficient constraints into a search space and
promoting effective exploration of it. In summary, their triangular model helped learners configure the search space for translating key sentences into formulae by defining the search space with effective constraints. This is the reason that their system worked well.

2.2 The Case of Declarative Knowledge

Next, let us consider conceptual understanding as an example of declarative knowledge. For example, imagine an ITS that supports understanding of concepts using tools such as mind maps and a situation in which the relationship (link) between concepts corresponding to a specific pair of two nodes cannot be understood by a learner. This is a so-called “Missing Link” problem. In this case, the set of all links assumed by the system (all links learned by the learner) forms the search space, and each link is located at a specific point within the n-dimensional space according to its features. The learner must choose the most appropriate one from them. If the learner says “I don’t know at all,” however, it can be inferred that it is impossible for him/her to become aware of the set (search space) in which the candidate links are contained, thus the next task of selecting a link from the set cannot be assumed explicitly by him/her. Thus, models of states of “not understanding” based on n-dimensional search spaces have broad generality and can be applied to states of “not understanding” in relation to many problems.

2.3 Multi-level Modelling

In addition, by modeling the imperfectness of the search space configuration, we can model the state of “not understanding” in terms of multiple levels according to how severe the learners’ level of “not understanding” is. Let us now characterize our model. There are two changes/shifts in our new learner modeling:

(a) From modeling of “understanding” to modeling of “not understanding”
(b) From modeling of what to understand to modeling of how to understand

The first shift is what we have been discussing thus far. The second one requires elaboration. Because most of the existing learner models fall within the scope of “understanding of something,” learner modeling has been necessarily domain-dependent, that is, any learner model pertains to how learners understand specific knowledge within a specific domain. This type of modeling cannot capture the state of “not understanding” of a learner independently of a specific domain. At best, it deals with a buggy model⁹ that is domain-dependent, and it is far from constituting a model of “not understanding.”

However, learners who need help experience issues mainly because they do not understand what to do/how to solve a problem or how to perform a given task. Many low-performance learners often find themselves at a loss (do not know what to do). We find some domain-independent factors here because modeling a state in which learners have no idea of what to do requires no domain-dependent knowledge. In addition to offering the ability to deal with a learner’s state of “not understanding” independently of a specific domain, the proposed model can also account for the degree of “not understanding.” The key is the fact that the degree of “not understanding” corresponds to how poorly learners understand the search space and/or how poorly the search space is configured. The following is a list of correspondence between a learner’s state and our model.

(1) Learners are totally at a loss = They have no idea of the search space itself or its dimensions.
(2) Learners are at a loss = Learners cannot configure a search space = They are not aware of which attributes/perspectives to select as the dimensions of the search space.
(3) Learners demonstrate some meaningful behaviors, but they appear almost random = The search space is too broad, so they need a set of constraints to control the search within the space = The search space is poorly configured.
(4) Learners demonstrate some meaningful behaviors but cannot find a solution = The search space is poorly configured with an incomplete set of dimensions = They can figure out some of the dimensions but some important ones are missing.

As discussed in 2.1.1 and summarized in Table 1, conventional modeling methods deal with knowledge and its applications within the search space that is assumed to be understood by learners. On the other hand, our modeling system deals directly with the search space itself. Therefore, our idea of modeling a state of “not understanding” is complementary to con-
3. Application to Feedback Generation

3.1 Multi-level Modelling

At first glance, it seems difficult to infer the state of a learner who is totally at a loss and to build a model of “not understanding.” However, this is not the case. We do not need any advanced inference mechanism to implement our modeling methodology. The basic idea of model-building is a domain-dependent procedure that can be implemented by employing a domain-dependent dialogue as follows:

Step 0: Prepare the necessary and sufficient dimensions and an appropriate search space spanned by them.

Step 1: Identify whether the learner is totally at a loss. This can be done, for example, by confirming directly with the learner whether he/she knows what to do when he/she gets stuck.

Step 2: Identify how well the learner understands the dimensions. This can be done, for example, by observing his/her behavior and asking direct questions about the dimensions of the search space.

Step 3: Identify which dimension the learner does not understand completely by observing his/her behavior or asking questions.

Although the above description of the model-building procedure is rough, it is not difficult to refine and adapt it to specific domain knowledge when required. At this moment, we suspect that it is extremely difficult to construct a generic modeling procedure using this framework without specifying a domain.

3.2 Feedback Generation

In general, feedback can be generated to help learners configure the search space and become aware of its dimensions according to their degree of “not understanding.” Let us return to the “Missing Link” problem in which the learner must select the most appropriate one from the links in the candidate list (the search space). If the learner says “I don’t know at all,” the system should consider it impossible for the learner to think of the list (a search space), thus he/she cannot be explicitly aware of the next task of selecting a link from the list. Then, the system can generate feedback, saying, for example, “Remember the links you have learned so far and select the most appropriate link out of them.” This seems to be problem-specific or ad-hoc feedback at first glance. Viewed from the perspective of our modeling method, however, it can be justified because it is a specialization of a scaffold as a support of search space configuration. The legitimacy of feedback can be ensured based on search space modeling.

After making the learner aware of the search space, the system might need to set a task of checking the applicability of the candidate links in order and judging their appropriateness by comparing the nature of the two concepts with the link-setting conditions. If the learner has difficulty with matching, the system can set a new search space.

In addition, in the case of the previously mentioned woodworking task, imagine that a learner can only modify the color, size, and weight of the object. In such a case, the system would give a hint, saying, “Consider the possibility of changing the location of objects.” This seems to be an ad-hoc scaffolding message that is domain-specific. However, we can explain such messages in terms of search space modeling to provide a convincing justification as follows.

The learner performs the search in a 3-D search space including only color, size, and weight. In other words, the learner remains within an imperfect search space that never leads him/her to the right solution. The solution to this task exists within the 4-D space including color, size, weight, and position. Inspiration could be provided by suggesting that the position axis was the fourth dimension of the search space, enabling the learner to configure the 4-D search space. Thus, such feedback could be helpful to the learner.

4. Discussion

4.1 Generality

The proposed method is based on the notion of a search space of GPS, which is very general. Therefore, it can be applied to almost all types of learning. This said, there is an exception. The basic assumption underlying the applicability of our method is that the learning
activity involves a search within a search space. Therefore, if a learning activity is very algorithmic, like routine training, our method will not be applicable.

4.2 Related Work

Needless to say, all the works on learner modeling are related to this research. Because they are too numerous and have already been discussed to some extent, we only discuss Malamed’s work on concept learning, as kindly suggested by the reviewer. Her method involves giving examples and non-examples and refining relevant and irrelevant attributes to properly illuminate a concept. If such attributes are treated as dimensions of the conceptual space of the target concept, the idea is like our method. What makes the two methods different is, however, the notion of the existence of a search space. Her method has no explicit notion of a search within a search space. As we have seen, our method enables us to help learners learn declarative knowledge by converting it into a search within a search space.

5. Conclusion

We have discussed a new learner-modeling methodology based on the concept of search space within the GPS. Because this research is in the early phase, no evaluation of this methodology is presented in this short note. Nevertheless, the main claim made in the research is relatively strong. It introduces two innovative changes, or shifts, in learner modeling:

(a) From modeling of “understanding” to modeling of “not understanding”
(b) From modeling of what to understand to modeling of how to understand

The proposed model enables an ITS to generate feedback for learners who are at a loss that help them configure appropriate search spaces within which they may eventually find solutions. The proposed method could help not only low-performance learners through the above-mentioned feedback but also enhance the theoretical foundations of several existing ITSs whose feedback sometimes appears ad hoc. As discussed earlier, some existing feedback can be interpreted as helping learners configure appropriate search spaces. Obviously, there remains much further work to be done. Developing an ITS as a concrete example of model-building within a specific domain and its method of evaluation must be the first task. The other is to provide justification for the feedback of some of the typical existing ITSs to enhance their theoretical value. The author is fully aware that these tasks remain to be completed in future work.

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