Model-based training of situated skills

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Abstract

Situated knowledge includes contextualised action and decontextualised description of knowledge. This is a significant distinction for developers of intelligent computer-aided learning (ICAL) applications. Most work in ICAL has attempted to decontextualise skills through descriptions such as rules and procedures because these are better understood and more suited to presentation through existing technology than the skills themselves. Here we discuss skills that are resistant to being decontextualised, and examine how techniques (model-based training) developed to teach decontextualised descriptions of knowledge can be used for training in communication and metacognitive skills. To support this approach to learning an ICAL needs a way to describe models of a problem in many different ways, and a way to explore models to learn about their underlying assumptions and their relationships to the problem context. A vocabulary for describing models, which serves as a cognitive tool for practising situated skills, and a model-based training system that supports this approach to learning are described.

Introduction

Research in intelligent computer-aided learning (ICAL) has helped to reveal many significant issues about the way people learn and solve problems, and about the role that technology can take to support people. One of the most enduring assumptions underlying the design of ICAL systems is that domain knowledge can be represented in symbolic models and that people can develop skills by learning these descriptions of knowledge (Anderson *et al.*, 1996). This assumption suggests first, that skills can be taken out of the context in which they are practised and taught by presenting descriptions of them, and second, that this is sufficient for training workers in the skills they need to be full participants in their community of practice. However, when faced with complex situations that demand a multitude of different skills it is evident that the

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knowledge needed extends beyond mere descriptions of rules and standard procedures. Besides technical skills, such as those involved in operating machinery, social interaction and communication in the work place are an important part of a worker's job. These skills are emergent properties of interaction between two or more people, and precisely for this reason it is difficult to model such knowledge in a single static model. Consequently, ICAL systems have mostly ignored this area of situated cognition and instead have concentrated on the more readily modelled descriptions of technical knowledge.

This paper draws attention to some areas of situated knowledge (metacognitive skills and affective skills) that have largely been ignored by developers of ICAL systems. It also supports a view that technology originally designed to support learning of technical knowledge can be used to help students develop aspects of situated knowledge. We focus on model-based reasoning and examine an instructional method that supports situated knowledge by providing opportunities for students to practice skills while performing authentic tasks.

Aspects of situated knowledge

When one refers to situated knowledge the intention is to highlight the spatio-temporal location of activity. Sometimes one refers to social knowledge to make a distinction between the affective domain (Krathwohl *et al.*, 1964) and the more commonly spoken about intellectual or technical knowledge. The word social should draw attention to the interactive, dynamic and participative character of knowledge. Context is important here. Knowledge that is intricately entwined with the spatial, temporal and environmental features of a situation can be thought to be contextualised, whereas knowledge that may be usefully isolated from such factors is decontextualised. Situated knowledge is not limited to just the contextualised; it includes all knowledge, specifically, it includes the decontextualised descriptions of technical knowledge. However, here we will distinguish two main categories of knowledge that possess, essentially, context. We include examples of *metacognitive* knowledge and *affective* skills. These are introduced in order to clarify what we mean when referring to metacognitive or affective skills. Later we discuss how these skills can be supported with model-based training techniques.

Metacognitive knowledge and context

Being aware of one's understanding and skills is called metacognitive knowledge and involves being conscious of the implicit assumptions and justifications in the practices of a community. That is, metacognitive reasoning involves thinking about the problem solving process itself, eg, why one approach to problem solving is preferred over another. It demands self-explanation (Chi *et al.*, 1989), flexibility and reflection (Schon, 1983/1991). A partial context can be added to descriptions of this kind of knowledge by associating the problem solving *methods* with the actual *knowledge* involved in solving problems and the *problem* itself, eg, in terms of conditionalised knowledge (Prenzel and Mandl, 1993), which sets conditions on the applicability of object knowledge (knowledge reasoned about by metaknowledge). Conditions allow knowledge to be partly contextualised so that its applicability is specified and associated with a description of a situation, a goal and other knowledge. However, other psychological factors (Norman, 1988), eg, stress levels, cognitive load, moods, etc., are essential elements of an authentic situation and provide valuable context. These factors are not easily described so condition flavoured descriptions of knowledge are not fully contextualised. Only during simulated or real activities in which the psychological, environmental and epistemic conditions are included is metacognitive knowledge fully contextualised. Context is also provided by the history of decisions made in a situation, such as the evolution of the problem as it is continually re-framed in terms of changing models. We will concentrate on this last aspect of context and describe initial results in developing a methodology to support model switching.

Affective skills

Much of the difficulty with modelling the affective domain arises from the ambiguous understanding most people have of such concepts as creativity, dynamism and conciliation, which makes it difficult to define them. Therefore, examples of affective knowledge must be used to refer to the concepts. However, an example of conciliation, for instance, involves more than just the *results* of the conciliation process; it must include the *process* itself: reconciling two alternative viewpoints. Neither is observing the conciliation process sufficient to develop conciliation skill oneself. What is needed is to be an active participant in the process of conciliation or any other affective skill. Only by engaging in the activity one wants to be proficient in can that skill be developed. Opportunities for practice are all important in learning affective skills; more so than they are for the intellectual domain since some intellectual knowledge can be learned from abstract descriptions out of context (Anderson *et al.*, 1996).

When attempting to develop a model-based training system for situated skills the stumbling block is in the difficulty with modelling knowledge. How does one describe the knowledge involved in a conversation between two professionals discussing a technical problem? Clearly there will be references to descriptions of technical knowledge, eg, operating procedures, rules-of-thumb and general principles. There will also be less easily described knowledge that enables the conversation to flow: certain protocols and cues for turn taking; understanding gestures and changes in intonation; and attitudes that affect the style of conversation, eg, argumentative or conciliatory.

All of these aspects of metacognitive and affective knowledge need to be investigated in order to provide computer-based support, although some work has already been performed here. For instance, the self-explanation effect has received a lot of attention (Chi *et al.*, 1989), and so has analogical reasoning (Schank, 1986), but communication and problem re-framing have not. Metacognitive reasoning is a difficult subject to support because it is hard to produce descriptions or models of this kind of knowledge. An even more evasive area is the affective domain, eg, attitudes, which involve tacit pre-dispositions to behave in a certain way. Metacognitve skills and affective skills have always been difficult to support with ICAL systems because they are so hard to articulate.

A practical solution to the problem of modelling metacognitive skills and affective skills is to avoid the need to model them at all. Model-based training systems can be developed that avoid the need to construct models of knowledge by using models consisting of descriptions of "technical" knowledge as cognitive tools for practice. Brahms (Clancey *et al.*, 1998) for instance, uses simulations to target the interactive elements of work practices rather than the technical descriptions of procedural work flows. In our work, a computer tutor can act as a shared workspace to aid representation and communication of different mental models. Because the target of instruction is the (contextualised) knowledge, choice of domain for decontextualised knowledge (descriptions) is incidental. What is important is that there be a rich variety of models available to allow discussion and negotiation to exercise the situated skills.

A multiple model architecture

In order to provide resources for practising situated skills, such as communication, a multiple model architecture is proposed in which a set of executable domain models describes the total *decontextualised* descriptions of knowledge. Interactions between the models, and between the user and the models represent the *contextualised* knowledge. Briefly, the totality of situated knowledge is learned with an ICAL by the student becoming familiar with the descriptions of knowledge contained in the models, and, very importantly, by developing the metacognitive skills associated with model switching (changing from one model to another), communication and other affective skills. Activities such as re-framing and restructuring of problems are achieved by changing models. When these are performed in the context of a discussion and a particular style of interaction is enforced, communication skills are practised too. Students should know how to identify appropriate models to begin problem solving from, learn when it is appropriate to change to a different model, and be able to communicate their reasoning so that the metacognitive basis of model switching is made explicit.

Models provide descriptions of a problem situation, which enable communication of mental models into a shared workspace. What is required of an ICAL to support this approach to learning is a way to describe models of a problem in many different ways (see modelling dimensions), and a way to explore models to learn about their underlying assumptions and their relationships to the problem context (see EXTRAS architecture).

A vocabulary for describing models

A model can be visualised as a geometrical shape with a number of axes or dimensions. It is easier to think of a cubical form with three dimensions (Figure 1), although there will be more than three dimensions in reality. Each dimension represents a significant decision point that helps to locate the model in the model space, which is a multi-dimensional space containing all possible models of a system or problem. In selecting a model, decisions will have been made about all the relevant dimensions that locate it. Or put another way, by choosing values for every dimension, eg, high, low, medium, for *resolution*, or component, subsystem, system for *scope*, one can navigate to a specific model in the model space. Neighbouring models will differ slightly–possibly by a value for only one dimension. More distantly related models will differ more. Therefore, the relative co-occurrence of values for dimensions is an indication of relative similarity of models.

Modelling dimensions

A set of properties, called *modelling dimensions* (Leitch *et al.*, 1992, 1995), represents fundamental characteristics associated with the context of a physical system or framing of a problem. Each dimension denotes a different context, eg, the mechanical processes might be the focus of attention in one model whereas chemical processes might be so in another. A few dimensions are discussed here and further details of the modelling dimensions can be found in Khan *et al.* (1998a). Scope, generality, and resolution are illustrated in Figure 1. Scope is concerned with the extent of the physical system or the problem being modelled. It accounts for spatial context so that the bounds of a system are set in terms of the components included in a model. Resolution dictates how much detail is included in a model. Several small components can be identified as individuals in a high resolution model, whereas a low resolution model would combine them all in a single unit. For example, a model of a library system may treat each book in the computing section as a unit component or it may group the entire section into a single unit called "the computing section." Finally, generality affects the cognitive efficiency of a model and provides some temporal context. A high generality model is relatively abstract and permits reasoning over a large number of similar situations but requires additional reasoning to establish a connection between the abstract representation and the world. In contrast, a low generality model is limited to a few problems but has a direct mapping to the world, that is, it has a more explicit context.

Each component cube fixes the values of the three dimensions just discussed, however, other dimensions still need to be set and this is represented in Figure 1 by the explosion of a component cube into another cubical structure. This time the three dimensions

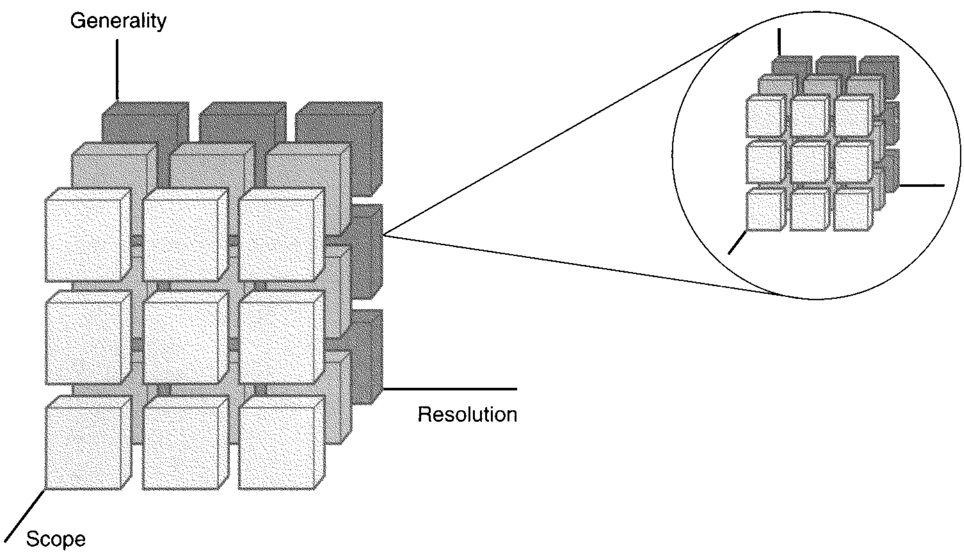

Figure 1: Multiple model cube–each cube comprises smaller cubes

are different, eg, ontology, level and orientation, and provide support for considering additional aspects of context. Ontology indicates the basic nature of the model in terms of what is relevant about the system, eg, mechanical, electrical, chemical processes. Level relates to whether meta-level knowledge or object level knowledge is being considered. And orientation refers to whether descriptive knowledge about the system is included or prescriptive knowledge about controlling the system. A further explosion of each component cube in this second level enables further contextual factors to be specified. Since each component cube of the overall cubical structure is itself a further set of models, each possessing certain values for dimensions, the process of moving around the model space is analogous to changing context.

Different positions along each dimension's quantity space produce models that represent different contexts. When these are communicated and discussed in a shared workspace they are treated as partly contextualised viewpoints of a situation. Each participant in a discussion can hold different viewpoints (different models) about the same situation so each can reflect on the choices made and the consistencies or otherwise in their viewpoints. It is also possible to change one's viewpoint, which enables students to experience the world differently, to notice similarities and differences not possible before, and to re-evaluate the priority given to problems and solutions. Indeed, learning to switch viewpoints in response to a changing context is an important objective of the multiple model approach to training.

Representation of models

Every model is represented in one of three ways: equations, production rules and procedures. Mathematical equations are used to state relationships between parameters and variables. Simulations frequently make use of equations for determining values of unknown parameters by solving equations at run time. Rules associate conditions with actions in IF-THEN constructs, and are commonly used in knowledge-based systems and expert systems. Procedures are sequences of actions and may be represented in petri nets.

EXTRAS–A simulation-based training toolkit

Figure 2 shows a description of the EXTRAS authoring toolkit, which includes the multiple model architecture for the domain system and an explanation/communication component. An application built from this toolkit serves as the shared workspace in which students and the explanation system can discuss viewpoints (models).

Several models of the system can be made available to the student to experiment with depending on what knowledge is available to the system developer. Operational models of expertise (prescriptive knowledge) and structural models of the plant (declarative knowledge) are described and used for providing the content of explanations. Each element of knowledge is described as a *knowledge filler*, which allows descriptions of multiple kinds of knowledge to be provided in a single explanation by combining several knowledge fillers. This process is explained more in Khan *et al.* (1997,1998b). The domain models are also used to evaluate the student's actions from a comparison with

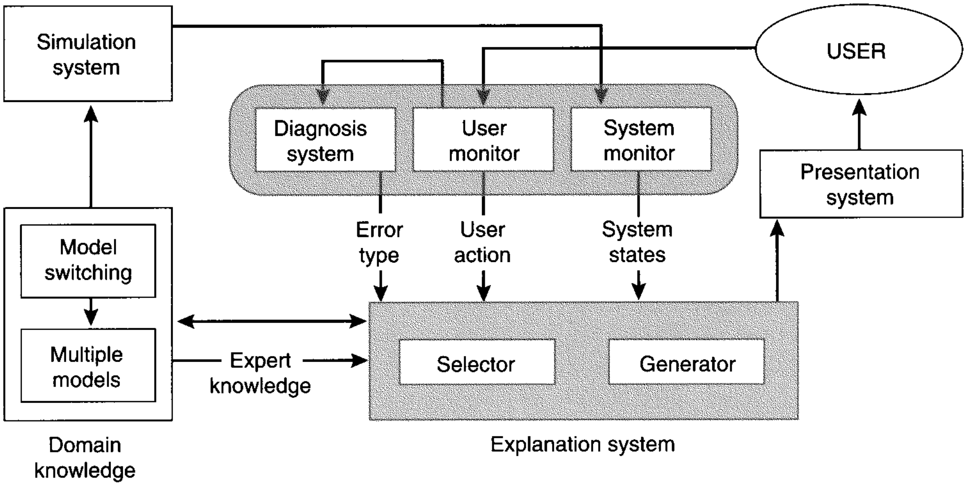

Figure 2: Architecture of training system

the recommended expert action. Any errors are classified as being of a particular type of *deviation* following the scheme presented in Hollnagel (1993). A prototype diagnosis system determines the cause of error, which is given as a classification over four options (Mitchell *et al.*, 1996).

Learning strategy

Instructional support is given by the explanation system whose primary method for support is through explanations that are chosen to stimulate the user into constructing a particular type of mental model. By placing demands on students for certain types of knowledge the intention is they focus on that particular *class* of knowledge (ie, a particular kind of model with its corresponding values for dimensions, eg, procedural knowledge at object level with high resolution, etc.), so that students learn to associate a kind of knowledge with the context in which that knowledge was chosen. In this way students develop metacognitive knowledge about the choice of models appropriate for particular contexts. It should be noted that the aim of the interaction is not necessarily to learn knowledge representations or the object level knowledge they describe, eg, the actual rules and procedures of a model, but to use them merely as symbols denoting the class of knowledge and the kind of model. For example, the student may need to understand that "higher generality" is needed in one situation, or "lower resolution" is sufficient in another. The objective is to associate positions on each of the modelling dimensions with the demands of the problem. This is valuable knowledge that will affect the efficiency of problem solving in future situations when model selection or problem re-framing is needed.

During instruction the domain system can be called upon to solve problems as an expert system (Ravindranathan and Leitch, 1996). However, unlike most systems the

EXTRAS domain system employs multiple domain experts and switches between them during problem solving. This facility is designed specifically to support students in developing model switching skills. Students can witness the metacognitive model switching process during an "expert demonstration" mode. They also get the opportunity to participate in a similar activity by solving problems themselves, either entirely, or by being responsible for re-framing the problem in the context of an evolving solution.

Interactions with the explanation system provide valuable opportunities for students to develop their communication skills, particularly question asking, and they contribute to students learning the relevant vocabulary for discussing professional matters. Discussions centre on the mental models that students have of the system, which can be reified by selecting one of the system's available models. Questions can be asked of the system concerning that model. For instance, students can ask for justification of rules that indicate the causality inherent in the system. A response can be to present another model, eg, equations that illustrate the causal connection through a simulation, which offers a more dynamic presentation medium than static descriptions.

Conclusion

We have presented a methodology based on modelling dimensions for supporting development of metacognitive and affective skills as part of situated knowledge. Changing models is valuable practice in avoiding rigidity and seeking alternatives during problem solving. By practising this on descriptions of technical knowledge students should learn that changes in models can be beneficial for solving complex problems. The purpose of the methodology is to help develop these skills by using the descriptions of knowledge as cognitive tools that can be manipulated in a shared workspace. Training systems based on this methodology are being deployed in four industrial applications in the process industries eg, energy generation (Caimi and Lanza, 1997). These systems will be used along with existing simulations to train operators in a range of different skills including developing model switching strategies and communication skills. In summary, interactions between students and the multiple model-based domain system are intended to help exercise metacognitive skills and communication skills in the context of authentic tasks.

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References

Anderson J R, Reder L M and Simon H A (1996) Situated learning and education *Educational Researcher* **25** (4) 5–11.

Caimi M and Lanza C (1997) Intelligent simulation systems: the EXTRAS approach *Proceedings of the Sixth European Conference on Cognitive Science Approaches to Process Control-CSAPC'97*, 103–106, CNR.

Chi M T H, Bassok M, Lewis M W, Reimann P and Glaser R (1989) Self-explanations: how students study and use examples in learning to solve problems *Cognitive Science* **13** 145–182.

Clancey W J, Sachs P, Sierhuis M and van Hoof R (1998) Brahms: simulating practice for work systems design *International Journal of Human Computer Studies* **49** 831–866.

Hollnagel E (1993) *Human Reliability Analysis Context and Control* Academic Press, New York.

Khan T M, Mitchell J E M, Brown K E and Leitch R R (1998a) Situated learning using descriptive models *International Journal of Human Computer Studies* **49** 771–796.

Khan T M, Paul S J, Brown K E and Leitch R R (1998b) Model based explanations in simulation based training *Proceedings of Intelligent 4th International Conference on Tutoring Systems*, ITS'98, San Antonio, Texas.

Khan T M, Brown K and Leitch R R (1997) Didactic and informational explanation in simulations with multiple models *Proceedings of 8th AIED*, 355–362, Kobe, Japan 1997.

Krathwohl D R, Bloom B S and Masia B B (1964) *Taxonomy of Educational Objectives: the Classification of Educational Goals: Handbook 2—Affective Domain* Longman, London.

Leitch R R, Ponnapalli P V S and Slater A (1992) The representation of domain knowledge in intelligent training systems *Proceedings of the 1st International Conference on Intelligent Systems Engineering*, 269–274.

Leitch RR *et al.* (1995) Modelling choices in intelligent systems *AISB Quarterly* **93** Autumn. 54–60.

Mitchell J E M, Brown K, Leitch R and Slater P J P (1996) MOBIT: Pragmatic Diagnosis for Industrial Training, 99–112 *The Intelligent Systems Integration* Program: Proceedings of Expert System 96, Cambridge, UK.

Norman D A (1988) *The Psychology of Everyday Things* Basic Books, New York.

Prenzel M and Mandl H (1993) Transfer of learning from a constructivist perspective *in* T F Duffy T F, Lowyck J and Jonassen D H (eds) *Designing Environments for Constructivist Learning* Springer-Verlag, Berlin, 315–329.

Ravindranathan M and Leitch R (1996) MuRaLi: an architecture for multiple reasoning. *9th International Symposium, ISMIS'96* 593–602, Zakopane, Poland. Springer-Verlag, Berlin.

Schank R C (1986) *Explanation Patterns—Understanding Mechanically and Creatively* Lawrence Erlbaum Associates, Mahwah, NJ.

Schon D A (1983/1991) *The Reflective Practitioner* Maurice Temple Smith, London.