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Applying Cognitive Science to the Teaching of Science

[Commentary on: Brna, P., Baker, M., Stenning, K. & Tiberghien, A. (Eds.) (2002). *The Role of Communication in Learning to Model*. Mahwah, NJ: Lawrence Erlbaum Associates.]

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Cognitive science would seem to have much to offer education. If cognitive science has truly enhanced our understanding of mental representation and cognitive processes then that enhanced understanding should surely support numerous teaching applications. In truth, however, applications of the results, and even the methods, of cognitive science to education are few and far between. It is thus refreshing to see an edited collection that deals explicitly with cognitive science and education. This collection, which stems from a conference held in Corsica in 1999, consists of a mix of chapters that apply cognitive science approaches to the understanding of learning in a variety of scientific domains and chapters that present and assess different computer-assisted learning environments.

The primary theme that links the chapters in *The Role of Communication in Learning to Model* is that understanding key phenomena in the various scientific domains is assumed to involve developing and being able to apply some kind of (mental) model of the domain. To illustrate consider the case of electrical current. Gentner & Gentner (1983) observed that students appear to reason about electrical current using one of two different "models": one in which the flow of electricity through a wire is seen as analogous to the flow of water through a pipe and another in which the flow of electricity is seen as analogous to the movement of a crowd through a corridor. Students may use the models to explain or rationalize the observed flow of electricity in various situations, and to predict how elements in an electrical circuit (e.g., batteries or resistors in series or parallel) may impact upon the flow of electricity.

Gentner & Gentner's 1983 paper was published in a collection under the title *Mental Models* (Gentner & Stevens, 1983). The contributions to that volume argued for the wide-spread use of mental models in everyday thought, and in the opening chapter Norman (1983) made the concept of a mental model explicit: "In interacting with the environment, with others, and with the artifacts of technology, people form internal, mental models of themselves and of the things with which they are interacting. The models provide predictive and explanatory power for understanding the interaction." [Norman, 1983, p. 7.] The intellectual roots of the present volume lie in this early work on mental models.

I have labored the relation to early mental models research because only one chapter in this book makes explicit reference to it – most contributions take the concept of mental model as given, and work from there. This is justifiable in the context of the conference that led to the book, but in the book itself it is a serious failing. First, it limits the book's accessibility effectively to those who are already familiar with the work of one or more of the contributors. The reader is often required to work hard to place the contributions in a wider cognitive science or educational context. Second, it is far from clear that the contributors actually agree on what they mean by modeling. In some cases modeling appears to amount to using an external representation (possibly maintained by a computer program) that is analogous to a target domain. Other cases seem to be more concerned with the development and manipulation of internalized representations that parallel a target domain. Even amongst the latter cases, there are no attempts to address questions concerning the nature of mental models. Again, reference to work in this area (and most notably that of Johnson-Laird, also published under the title *Mental Models* in 1983) is surprisingly absent.

Secondary themes running through most of the chapters are those of communication and learning. Communication is defined in a broad, almost information-theoretic, sense, and a strength of several contributions is their analysis of different forms of communicative interaction during learning episodes. Interactions between teachers and students, students and other students, computers and students, and even student teachers and their supervisors are all analyzed at various points. The different roles played by participants within communicative interactions are also analyzed with respect to their effects on knowledge and its organization. Many contributions stress that there is more to learning than acquiring knowledge, and discuss how different kinds of communicative interaction may trigger knowledge restructuring or reorganization. Again, however, links to wider literature (this time the developmental literature, and notions such as representational redescription – Karmiloff-Smith, 1992) are curiously absent.

Coordinating representations

In the opening chapter, Stenning, Greeno, Hall, Sommerfield and Wiebe argue that we must frequently deal with multiple representations of the same situation. Textual and graphical representations are the prototypical example. A major task facing a child learning about a domain is to understand relationships that hold between different representations. Stenning *et al.* argue that this learning is demonstrated by children's communicative interactions during learning episodes. They support this position by presenting a detailed case study of a group of children learning about population modeling. The children used a simple population modeling simulation tool to study how interactions between two species (prey and predator) influenced the population of each. Over a six-week period the children learnt about concepts such as exponential population growth, predation, effects of resource limitations, steady states and extinction. Qualitative analysis of dialog and video from various points in the period illustrates not just conceptual development, but also how children use communicative interactions to coordinate the various representations. A major subtext of the chapter is that these communicative interactions may be analyzed at different levels – at a purely semantic level, at the level of individuals within the group, and at the level of the group as a whole – but that interactions between these levels can be crucial to fully understanding the processes within a learning episode. The point is well made, but the pedagogical implications are not explored.

Vince & Tiberghien provide an alternative perspective on coordinating multiple alternative representations in the second chapter. Their theoretical approach is more explicit and more formal, yet also more narrow. They analyze the problem of learning to model within physics as one of aligning two bodies of knowledge: one of the target physical domain (e.g., the nature of sound waves) and one of relevant general knowledge. In the case of sound waves physical terms with precise definitions (e.g., frequency, amplitude and spectrum) must be related to commonly used labels for similar concepts (pitch, volume and timbre). Given this analysis, communicative interactions may be categorized as belonging to the domain of general knowledge, belonging to the domain of physical theory, or as linking the two domains. The second part of the chapter presents SimulaSON, a computational environment for teaching the physics of sound based on the analysis and the possible forms of interaction between the domains. The environment may well be a useful pedagogical tool, but the authors fail to present any real evaluation. This results in a chapter whose two halves are poorly linked. It also feels like a missed opportunity, for a successful evaluation of the environment would serve not only to promote SimulaSON, but also to validate the authors' theoretical position of learning to model as one of aligning bodies of knowledge.

Chapter three, by Frederiksen & White, is in my view the most complete of the opening chapters. The authors focus on the domain of simple electrical circuits, and begin with the observation that much teaching of concepts in this area uses multiple models of varying abstraction but fails either to acknowledge the existence of alternative models or the relationships between them. The point is made by a list of seven different models of electrical circuits, including physical models, causal models, quantitative models, production system models and circuit diagrams. Frederiksen & White then go on to demonstrate (using standard experimental methodology) how use of a computer simulation environment that emphasizes relationships between two important classes of model can enhance students' understanding of the domain. The chapter's strengths lie in its relation to main-stream cognitive science (the use of widely-accepted experimental methodology and relatively good contact to wider modeling and developmental literatures) and its obvious pedagogical relevance.

Modeling environments

The central section of the book consists of four chapters that present and evaluate a variety of computer-assisted learning environments. The section begins with a chapter by Luckin & de Boulay in which the authors relate their experience with two computer-assisted learning environments, EcoLab and Galapagos. The former is aimed at children aged 10 to 11 and allows the exploration of simple eco systems. The latter is aimed at older students (aged 15 to 21) and intended to support the collaborative production of a scientific essay on aspects of evolution. The systems have very different aims and cannot be directly compared. Instead the authors analyze learning styles within each age group. Students are described in terms of their interaction profiles and their collaboration profiles, but ultimately the paper is descriptive. While different profiles are discriminated, the profiles remain purely theoretical constructs and their predictive or explanatory value is not assessed.

In chapter five Fund adopts a more traditional approach to the evaluation of a learning environment. She presents a quantitative study of the effects of different problem-solving support regimes within a computer assisted general science environment. The support regimes, which were implemented via different (but overlapping) sets of guidance questions, were found to influence the information search strategies employed by participants (who were high-school students of varying ages). Fund argues that guidance questions that trigger reflection and meta-cognitive processes result in more effective information search strategies (hierarchical search rather than linear or random search), and more systematic use of "external representations" (i.e., notes). The clear implication is that such questions also result in more effective learning, although actual learning success does not appear to have been measured.

The sixth chapter, by Bouwer, Bessa Machado & Bredeweg, differs in character to all others in the book (though it bears some similarity to the second half of chapter two). It aims simply to present two model-building environments. While there is some theory behind the environments, the approach is primarily descriptive. The first, VISIGARP, is a visual front end to an existing simulation environment (GARP), while the second, MOBUM, is an object-oriented system that aims to support "learning by building". Precisely what the authors mean by this remains unclear. Both environments appear to be useful tools for developing domain-independent qualitative simulations, but the themes of learning and communication, evident in most other chapters, are largely absent.

The section ends with a discursive chapter by Bull, Dimitrova & Brna in which four computer-assisted learning environments are described and contrasted. The environments include purely text-based systems (appropriate, for example, for language learning) and systems that mix text and graphics. Some maintain user-models – models of the student interacting with the system – and employ these models to guide learning by, for example, forcing the student to reflect upon areas of weakness in their knowledge. Other systems are designed primarily for collaborative use. The authors see strengths in each of the environments they describe, arguing that each addresses different aspects of learning. They conclude by championing the development of a hybrid system that incorporates key aspects of each of the four environments. Certainly elements of the various environments appear well motivated – user-models are important for producing a system that can adapt to different learners and the changing needs of single learning, while reflection in the form of self-explanation has been shown to improve learning (Chi *et al*., 1994), and several chapters argue for the need to support collaborative learning – but the argument that all features can and should be incorporated into a single general learning environment is weak.

I found these four chapters problematic. There are no explicit links to earlier chapters (or later chapters for that matter), and the level and form of evaluation differs markedly across chapters. Fund's chapter is the only one that really attempts a scientific evaluation, but even there the evaluation is not so much of a learning environment as of a supplement to that environment in the form of guidance questions, and the primary outcome – that provoking reflection is a good thing – echoes a well-known result (Chi *et al.*, 1994).

The role of language in collaborative modeling

Section three of the book turns to issues of collaborative modeling. Brna & Burton, in chapter eight, concern themselves with modeling interactions between students who are themselves developing a model (i.e., modeling modelers). After isolating several features of collaborative model building (e.g., relating internal and external representations, constructing and using artifacts, negotiating joint agreement), the authors describe Clarissa, an agent that interacts with other Clarissa agents in building a model (in this case of an electrical circuit). Clarissa agents use a co-constructed external representation to coordinate their interactions (rather than beginning with an explicit plan) and can take a number of interactive roles (questioning, responding, checking, arguing). The paper discusses how different interaction styles between Clarissa agents (e.g., polite interaction, where agents adopt a single role throughout an entire episode, or turn taking, where agents periodically swap roles) lead to different patterns of interactions and suggests that some styles (notably those in which most parties adopt most roles at different times within an episode) are pedagogically better than others. The results have interesting consequences for the design of collaborative learning environments.

In chapter nine Lund presents an analytic method for studying collaborative learning interactions. The method is illustrated through a case study of student teachers designing, executing and reflecting on a (physics) teaching assignment. The emphasis is again on reflection, and Lund draws upon ideas from Vince & Tiberghien (chapter 2) to partition entities into those from the observable world, the world of physics, and links between the two. She stresses the pedagogical importance of keeping different types of entity distinct, and demonstrates how teachers may become aware of students' misunderstandings by analyzing their discourse with these distinctions in mind. Lund's analytic method also highlights the importance of distinguishing between that which is to be explained and that which is the explanation, the tools and media involved in the learning situation, and the socio-institutional roles that students play in collaborative learning. The method aims to ensure that teachers consider the models that students develop, and to consider how the questions that they as teachers ask relate (either positively or negatively) to the models developed by their students.

In the penultimate chapter Alamargot & Andriessen review the cognitive effects of language production and attempt to apply findings from this area to the design of computer supported collaborative learning environments. The main finding is that the act of producing a written text can result in learning, possibly by triggering restructuring of knowledge. Writing is argued to be beneficial because it allows reflection on what is written: multiple drafts may be produced with progressive restructuring and reorganization of the content during the writing process. Writing thus supports reflection (which several chapters argue is critical for learning). Alamargot & Andreissen's ultimate recommendations are a bit banal: essentially they revolve around discouraging oral communication (even though technological advances will soon make learning environments with such facilities feasible) and providing learners with tools to support written communication.

The book ends with a chapter by Baker that focuses on the role of argumentation in learning. Baker draws upon examples from interactions between students learning to model in several physics domains. He argues that argumentation frequently involves clarification of the meanings of terms, but that such clarification may be positive (e.g., forcing one to elaborate ones thoughts and hence possibly discriminate between previously undiscriminated related concepts or to form new abstractions over related concepts), but that it may also be pedagogically counter-productive, as when a student may use argumentation to avoid confronting complex conceptual issues. The pedagogical message is clear: argumentation is productive when it prompts reflection, but counter-productive when it is becomes a defense.

Concluding remarks

As may be clear from the above, this is an eclectic collection reflecting the range of differing concerns and positions of authors one might expect at any conference. A number of themes surface in different sections of the book. The opening chapters establish that learning involves multiple representations and understanding relationships between these representations is critical. The central chapters focus on the use of modeling environments in teaching and learning situations, while the closing chapters address issues arising from modeling in collaborative learning situations. Pedagogical concerns are evident throughout the entire book, with the importance of promoting reflective thinking being stressed in several chapters.

The book includes many valuable contributions, but the general coherence across the chapters is low. While some key issues are highlighted in the preface, I feel that something more (such as introductory and concluding chapters) is needed to improve the collection's accessibility and ensure that it lives up to its potential. To give just one example, chapter ten argues against the use of purely oral communication on the grounds that written communication provides more opportunity for reflection, while chapter eleven stresses the potential benefits of argumentation (that, in the examples given, arises in an oral context). One might hypothesize that both modes of interaction engender reflection which in turn can prompt reorganization and restructuring of knowledge – something that studies of expertise tell us is a critical aspect of learning. However there is no place in the collection for this hypothesis to be proposed or discussed. The reader is left to draw all the strands together, when the editors are surely better placed to do this in an authoritative way. It is perhaps too much to ask for a collection of this sort to yield a single, coherent, theory of the role of communication in learning to model – indeed, the contributions demonstrate that communication may play many roles in learning to model – but the editors appear to have missed an opportunity to lay out their vision for the development of the field.

A second criticism concerns the range of different methodologies employed by the contributors. Some adopt the tried and trusted methodology of quantitative experimental psychology, but others adopt a more discursive, qualitative approach, and some are purely descriptive, presenting modeling environments with no attempt at evaluation. One might view this methodological pluralism as a positive sign of a community that is open to ideas from a variety of sources. A less generous view is that it is symptomatic of a field that has no clear direction. My feeling is that it is suggestive of a field that has yet to mature. The discursive qualitative analysis has an important role in generating hypotheses, but the established methodology of quantitative experimental psychology appears to offer the most hope for specifying robust principles that may be applied in the development of pedagogically sound computer-assisted learning environments.

In sum, this is a book with two significant weaknesses. It side-steps important issues, such as the nature of mental models, and it makes limited reference to some relevant literatures. However, these weaknesses do not fundamentally undermine the text. Indeed, they are compensated by the serious application of the methods, and in some cases even the results, of cognitive science to science education. This is an important area for cognitive science applications – one where more work could only be welcome.

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