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Model based learning as a key research area for science education

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A framework is presented for thinking about cognitive factors involved in model construction in the classroom that can help us organize the research problems in this area and the articles in this issue. The framework connects concepts such as: expert consensus model, target model, intermediate models, preconceptions, learning processes, and natural reasoning skills. By connecting and elaborating on these major areas, the articles in this issue have succeeded in moving us another step toward having a theory of conceptual change that can provide guidance to teachers in the form of instructional principles. Taken together, the articles remind us that individual cognition, while not the only factor in learning, is a central determining feature of learning. However, we must work to further develop the present partial theory of conceptual change to fill in the missing cognitive core of the present shell.

Introduction

Cognitive questions about the nature of learning and conceptual change have been complemented in recent years by many other categories of questions including those concerning metacognition, social learning processes, and affective processes. In fact, judging by the number of articles being written about metacognition and cooperative learning currently, one wonders whether these factors are now considered to be more important than cognitive factors. The articles in this issue, taken together, remind us that individual cognition, while not the only factor in learning, is a central determining feature of learning, and that we still have a great deal to learn about it. The articles speak to unanswered questions at the cognitive level that are centrally important and that could make a significant contribution to theories of instruction if we can make progress on them. Among these are: What is the role of mental models in science learning? What is the nature of these models as knowledge structures? What learning processes are involved in constructing them? What teaching strategies can promote these learning processes?

Recognition of the central import of conceptual models in the thinking of expert scientists was advocated early in the 20th century by Campbell (1957) who argued that elastic particle models of a gas go beyond a mere summary of what can be observed and constitute a separate level of thinking that explains the empirical observations. Here I will call these explanatory models. Harre (1961) and Hesse (1966) argued that such models often utilize an analogy to a familiar conception like billiard balls, and allow one, in Nagle's (1961) terms, to 'make the unfamiliar familiar'.

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These issues are of interest to science educators because of the suspicion that conceptual models can be important for the attainment of 'conceptual understanding' in science at a level that goes beyond memorized facts, equations, or procedures. The hope is that such understandings not only lead to a student's perception that science can 'make sense' via satisfying explanations, but also embody a form of flexible knowledge that can be applied to transfer problems. Exactly how this might happen using conceptual models has not been fully investigated. Consequently a number of the articles in this issue attempt to illuminate different aspects of conceptual models or how they are learned.

For the most part, the articles in this issue are primarily concerned with content goals, with a few exceptions such as the Buckley article, which looks at both content and process goals. We should welcome contributions to either topic, since both types of goals are important, although it remains an open question as to whether instruction should be designed to deal with both types of goals in any one lesson or specialized to deal with one type of goal.

A basic theoretical framework for model based learning

Developing such models through instruction can turn out to be surprisingly difficult, for several reasons. Hidden explanatory models cannot be observed directly. Students may be accustomed to learning at a more superficial level. New qualitative models may conflict with pre-existing intuitive models, requiring a conceptual change or reorganization to take place. Specialized vocabulary for describing the models may conflict with the meanings of terms used in natural language. A simple framework shown in figure 1 for thinking about modern approaches to model construction in the classroom can help us organize the research problems in this area, by focusing on several different issues. This framework is designed for educators with specific content goals:

- The framework specifies the goal of a *target model* or desired knowledge state that one wishes students to posses after instruction. This may not be as sophisticated as the *expert consensus model* currently accepted by scientists. In addition to (or at some age levels, instead of) logical relationships in formal treatments of the topic, an educator's view of the target model may need to reflect qualitative, simplified, analogue, or tacit knowledge that is often not recognized by experts.
- The framework includes a map of the student's *preconceptions* and natural reasoning skills present before instruction; the preconceptions should

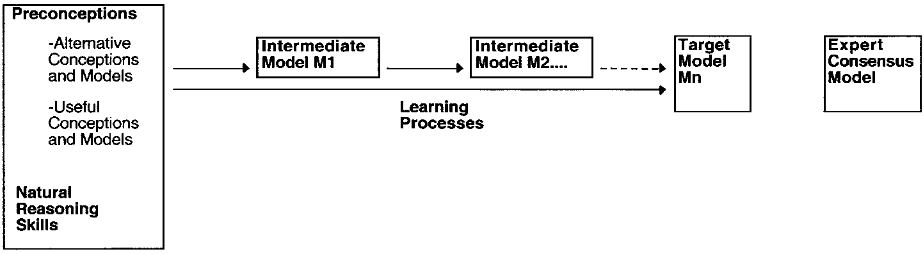

Figure 1.

include both alternative conceptions which are in conflict with the target model, and useful conceptions that are compatible with current scientific models and that can be used as building blocks for developing the target model. Intuitive, self-evaluated preconceptions that play an important role in developing a model have been termed anchoring conceptions (Clement *et al.* 1989). These two kinds of preconceptions can strongly influence the students' learning. A more encompassing concept for describing the 'mind-set' that the student enters the classroom with is termed the students' 'conceptual ecology', which includes the student's disposition toward the social and practical contexts present in the classroom as well as metacognitive beliefs and attitudes. Preconceptions and natural reasoning processes comprise the cognitive side of a conceptual ecology and will be our focus here.

- The framework includes *learning processes* that can take the student from preconceptions to target models. This may occur via one or more *intermediate models* that serve as partial models on the way to developing the target model. (In the end, whether the target model replaces, dominates, or coexists with initial alternative conceptions is an empirical question that may depend on the domain.)

This provides a framework for thinking about cognitive content learning events in individuals. More encompassing ones have been suggested (see Smith *et al.* 1993, Strike and Posner 1992), but in the pursuit of clarity, it serves here to provide an initial foundation and basic vocabulary for comparing the articles in this issue. At any point in time, instructional efforts will be directed at moving at student from model M_n to model M_{n+1}. The sequence of intermediate steps from preconceptions to target model form what Scott (1991) and Niedderer and Goldberg (1995) have called a learning pathway. For any particular topic, such a pathway would provide both a theory of instruction and a guideline for teachers and curriculum developers. The problem is that there are few topics for which we know enough about students' preconceptions and even fewer where we know enough about the best choices for other entities in the framework to guide curriculum development or instruction in a principled way.

Collectively, the articles in this issue represent a step toward developing a cognitive theory of conceptual change to the point where they can provide guidance to teachers in the form of such instructional principles for reaching content goals. I believe that the cognitive piece of that theory will not be sufficient for this task, but that it will be centrally important to it. That is, cognitive descriptions of learning processes, prior knowledge, natural reasoning skills, intermediate models, and target models will be centrally important. In addition, Harrison and Treagust, and to some extent Justi and Gilbert, deal with metacognitive factors. By and large, the articles do not deal with social or situated learning factors.

Buckley

Models as central to inquiry cycles

It is heartening to see Barbara Buckley in her article responding to so many of the challenges posed by the preceding framework. A unique contribution of this article is the hypothesized picture it paints of how a student's model can serve as a central guidepost for sustaining very open, student directed inquiry investigations. Her case study of a 16 year old named Joanne pursuing questions about how the human heart works constitutes a kind of ‘existence proof’ of the import of models and modelling in learning. Joanne’s model appeared to be a central point around which to organize new information, and it allowed her to answer transfer questions in a flexible manner. Buckley describes how her partial model at different stages appeared to lead her to generate new questions about the heart which sustained her in an inquiry cycle of question generation, investigation, and model revision. In biological systems ends are usually means for another end, and so it is with Joanne’s model of the heart: her current partial model is the centre of her current understanding but it also acts as a means by allowing her to effectively engage other material. It is not only a source of comprehension but also a source of new questions. That is, her model appears to generate new questions that enable her to maintain a cycle of model generation, criticism, and improvement. This cycle is not only worthwhile as a process goal in itself but it is critical in a student-directed setting for attaining conceptual change. Often we say that certain processes are centrally important in attaining content goals, but this is an example of content being central for attaining the processes involved in self-directed learning. The case speaks to the interdependence of content and process goals. It uses to best advantage the technique of the case study: although we cannot generalize the empirical results statistically to a larger population, we can use it to map out grounded hypotheses for knowledge and learning structures and processes.

The fact that Joanne was given a choice, chose to work alone on her project, and excelled over other students can serve as a provocative counterexample for social learning theories that are too all-encompassing. In her case it appeared to be her own progressively elaborated conceptual model that guided further learning, rather than the motivation of working with and responding to a small group collaboration.

New notations

Buckley develops a number of innovative notations for visualizing elements of the framework that I developed in section one of this commentary. The notations can be used for representing richly connected causal systems in biology at several different levels.

Techniques for describing target models and post conceptions. A representation not included in my figure 1 is a map of the student’s post model after instruction, which may or may not be similar to the target model, depending on the success of the experience. Buckley shows one method of doing this in biology in her figure 8, including distinctions between structure, function, behaviour and mechanism. Her diagram notation holds promise for allowing us to describe pre- and post- conceptions at an intermediate level of detail, and to compare them to a target model. The same notation can be used to represent expert models.

Buckley calls for more complete descriptions of target models in the curriculum and in research papers, saying: ‘Here the desired outcome is not a list of discrete, measurable objectives but an integrated model of the desired understanding similar to the display of the model-building learner’s knowledge.’ So her objective is an internal, integrated, and deeply understood model that the student can use to reason with and make inferences from. Because a named part of a structure at one level can be expanded to have a substructure with function, mechanism, and behaviour at another level, her notation implies a richly interconnected model that allows the student to give explanations at different levels. We might describe the interconnectedness she emphasizes as a kind of 'vertical integration' between levels. I believe that our field is sorely lacking in ways to represent complex knowledge structures, and this notation provides an interesting new contribution.

Overall map of learning processes. We not only need better maps of knowledge structures but also of learning processes and teaching strategies. The form of a learning cycle for model based learning is shown in Buckley's figure 1. It reflects the fact that Joanne revised her model many times during her work on this unit. It portrays the extremely important notion that models can be evaluated and revised repeatedly during learning.

Detailed maps of elements of learning processes. Her table I is a summary of some of the factors that influence a viewer's interaction with an illustration, which is a learning process at a finer grain size than the overall model construction cycle above.

The above list gives us a good start on a typology of types of information that are crucial to curriculum design and that are now accessible in studies that use qualitative as well as quantitative methods and that generate theoretical descriptions of knowledge structures and learning processes.

Misconceptions and analogies. Her discussion of the student's misconception of blood cells passing through capillary walls to deliver food to cells is quite revealing. She conjectures that it may have derived from an animation involving a visual metaphor of the bloodstream delivering 'steaks' which enter the cells. This reminds us that visual analogies in multimedia setting will have the same strengths and weaknesses of ordinary verbal analogies with respect to content goals. On the one hand they can foster understanding by tapping into rich prior knowledge schemas of the learner. But on the other hand, the limitations of the analogy must be clarified, and students' interpretations must be checked to see whether they have imported unintended implications from the analogy to their working model.

In sum, Barbara Buckley has provided us with some interesting new notation systems for unpacking and describing each of the critical elements in figure 1. Her case study of Joanne provides an existence proof of primarily student directed, solo, model based learning with many model revision cycles and impressive learning outcomes. Using Buckley's notation as a springboard, further knowledge structure notations should be developed to display causal relationships in more detail (see Driver 1973, Forbus 1984, Jackson *et al.* 1995, Rea-Ramirez and Clement 1997, Barowy and Roberts 1998). If sufficiently transparent notations can be developed, they should facilitate teachers' understanding of expert consensus models, target models, and students' understandings.

Janice Gobert

Janice Gobert's article in this issue on 5th graders learning about plate tectonics from tutorial worksheets and drawing exercises is an interesting study of conceptual change learning. Empirically grounded contributions to developing theory elements that expand my figure 1 are also made by her article. She does this by:

1. (1) Identifying *three types of information involved in conceptual models* of increasing sophistication: spatial, causal, and dynamic. One can then imagine a series of intermediate models going from left to right in the middle of figure 1 as the student's model is modified and improved. Gobert contends that students may naturally progress by starting from a spatial model of the elements in the system, and gradually adding more and more causal and dynamic properties to the model, giving us a more detailed picture of what the learning process of revising intermediate models is like. For example one needs to have a spatial model of layers in the earth before one can develop a causal model of convection in one layer (the mantle) driving movement in another layer (the crust).
2. (2) Elaborating on the idea of an *integrated model*. Different parts of the model should also become better integrated, so that the student can generate linked causal explanations that connect them, as one progresses from left to right in figure 1. Unfortunately there are many uses of the term 'integrated' being used in educational theory. I believe an important meaning in the context of model based learning is the idea that students must learn to be able to think with chains or networks of causal relationships that are larger than a single A causes B relation. To the extent students can do this, they have established an integrated system of individual causal relationships. When this occurs within one level of explanation, I call it 'horizontal integration'. Students can have a surprising degree of difficulty with this. This provides a key characteristic for thinking about desirable features of target and intermediate models in figure 1.

These factors involved in learning processes for constructing viable models have educational implications. One is that establishing a viable spatial model early in an instructional unit can be crucial to the rest of the unit. Because teachers do not generally receive enough feedback from students to know how their mental models may differ from the one the teacher is using, more feedback mechanisms are needed. This is one of the reasons Gobert recommends the use of student generated drawings along with student generated explanations. Because the drawing medium is presumably linked naturally with internal spatial models, asking for student drawings also *keeps the instruction focused* on developing a spatial and causal/dynamic model, as opposed to simply memorizing vocabulary phrases. *A coherent and continued focus on the developing conceptual model* was the most important facilitative characteristic Barbara Buckley identified in her case study of Joanne - the student in her sample who made the most impressive conceptual progress in an open ended learning environment. In Gobert's 'drawing to learn' strategy, students and the teacher can refer back to previous drawings as a readily accessible record of prior thoughts. Thus drawings can become a kind of glue that holds the instructional session(s) together, keeps them coherent, and focuses them on the developing conceptual model. This may be a larger sense in which drawings can be an *integrative medium*.

The Gobert study carries one very optimistic message: young students (in 5th grade) can construct mental models of complex causal and dynamic systems which they can then use to make inferences. This is true even when the models are explanatory models of hidden processes that are at a huge scale and can never be seen. This is tempered by the finding that not all students do this equally well. The factors that are responsible for these individual differences are still in need of investigation, but the potential for learning of this kind at this age level appears to be there.

The Buckley and Gobert studies utilize a very interesting paradigm for empirically grounded research on learning or teaching mechanisms: studying students going through a teaching unit and measuring the outcome of whether learning occurred quantitatively via a pre and post test, but analysing the intervening data qualitatively for information about powerful or faulty learning mechanisms that determined the outcome. This method has the potential to generate new insights about learning mechanisms that have initial grounding in case study observations. Methodology for the qualitative aspects of this type of study has been discussed recently by Clement (2000), Lesh and Lehrer (2000).

Harrison and Treagust

The article by Harrison and Treagust takes on the daunting task of attempting to grapple with the many senses in which the term 'model' is used in educational theory by proposing a descriptive taxonomy of models used in teaching. In some sense, this problem is almost as large as the huge problem of developing a coherent theory of knowledge structures before and after learning. Therefore we must view their effort here as a starting point. Their taxonomy allows them to discuss three important implications for teaching. First, they suggest that students begin with more concrete scale and iconic models before progressing to more abstract or mathematical models. This suggests another dimension along which the intermediate models in figure 1 can progress.

Second, they raise the issue of strengths and limitations of student generated analogies (as opposed to analogies generated by the teacher). Harrison and Treagust conclude that having students generate their own analogies increases student ownership, but that such analogies are often inappropriate for building a more expert like model. This leads the authors to recommend the careful planning of teacher generated analogies. They suggest a sequence in which an analogy is presented, but then mapped to the target phenomenon in discussions, with the students doing much of the mapping. Finally, limitations of the analogy are discussed. This represents a compromise in which the teacher takes responsibility for selecting the analogy, but the students are actively involved in completing and evaluating it. A similar approach with perhaps even more student evaluation is described in Clement (1993). That article illustrates how several analogies can contribute to the developing intermediate models in figure 1.

Third, they point out that there is a metacognitive problem in using models in science teaching in that 'most secondary students believe that there is a 1:1 correspondence between the models they use and the targeted reality'. They state that 'students need epistemologically guided lessons on how to construct and interpret analogical models'. One way I interpret this is to say that many students are not sold on figure 1 as a picture of what they are supposed to be doing in school. The idea that future models will supersede the current expert consensus model is not intuitive. They may think of learning as memorization of the expert model rather than model revision. And they may be impatient with the idea of learning one or more intermediate models as stepping stones to a more sophisticated model. They might say: 'Why not save time and just memorize the final target model?' Harrison and Treagust's suggested remedy is that students need to develop more sophisticated views of how science is learned, along with the content itself. This suggests a parallel track to the progression shown in figure 1, in which the students' awareness of how science progresses and a metacognitive sense of how they learn become more sophisticated with time. This is one of the ways in which the student's conceptual ecology should change that goes beyond a strictly cognitive approach to content learning and begins to include metacognitive considerations.

Beverley France

The most interesting question raised for me by Beverly France's article on curriculum development in biotechnology in this issue is whether engineering principles for solving specific design problems are very different cognitive entities from scientific models for understanding a domain. For example, is a flow chart of how goods progress through a drug manufacturing process the same kind of entity as a scientific model? Before reading this article I would have disagreed, but after reading it I am persuaded that it has many of the same features. It is a causal model, albeit one for a very specific situation. It is a simplified representation of complex system. It may even represent processes such as biological changes that are ordinarily hidden to observation.

The most striking difference between these technology models and scientific ones is the more general, broadly applicable nature of scientific models. Once understood, a technological model will not be as generally useful and transferable as a more general scientific model. But if students learn something about the process of model construction in a meaningful context, then technology models still have much to offer in education.

The France article stretches our concept of what a conceptual model is into the realm of industry and technology. But similar issues apply. Model criticism and revision cycles during the development or learning of a model of an assembly line may occur just as in pure science models. One may need introductory, intermediate and final target models, as well as analogies as in figure 1.

Like other models, biological models are simplified descriptions of a complex reality and can be particularly brittle when ideal conditions break down in industry for example. This provides an opportunity to have students discuss the purpose and limitations of a model, and the possibility of having different models of the same system for different purposes. Thus they may be a good area to develop the student's awareness of the nature of models - so that instruction in France's words: '. . . will enhance students' appreciation of the role of models being not just a representation of reality but a mean of approaching intellectual problems'. The most general educational implication of these considerations for me is that engineering models may provide students with a more concrete entry point for experiencing model construction. This follows the recommendation of Harrison and Treagust in this issue that students be introduced only gradually to more abstract models. However, while they appear to be talking about abstraction as a property of the expressed symbol system being used, I am here referring to perhaps a different sense of the term in speaking of the generality of the models being constructed.

Thus Beverly France's article provides an important example of an approach to the more general problem of how to situate instruction about models in practical contexts that are meaningful to students and connected to their lives.

Jennifer Snyder

Like Buckley and Gobert, Snyder attempts to characterize different features of internal representation systems in science. However, she does this by comparing novice, intermediate, and expert subjects. Since novice subjects have had some initial instructional experiences unlike naive subjects, these representations would lie in figure 1 on a spectrum starting from a point to the right of Preconceptions and stretching to the Expert Consensus Model. By using a problem sorting paradigm where subjects are asked to place physics problems in groups and label the groups, her point of departure is on properties of the problems rather than the internal representations themselves.

This article represents an attempt to refine a theory of one aspect of expertise that has been with us since the work of Chi *et al.* (1981). Experts are said to be more theory or model based in their approach to problems than novices, who tend to focus on surface features of the problems. This provides another interesting dimension to think about in the progression of models shown in figure 1. Each of the boxes shown there are supposed to be sets of knowledge conceptions that can be applied to problems - but how does the subject know which conception to apply from within the set? Each conception must have associated with it something that tells the subject an appropriate domain of application for that conception. Whether this has to do with surface features or more abstract features of the problem is crucial from the point of view of the authors' framework.

Snyder proposes that expert knowledge is more theory based than Giere (1988) predicted in his work on the nature of models in science. Her analysis assumes that problem classifications that involve mentioning attributes like gravitational force and friction force are theory based. It is unclear as to whether these would be considered attributes associated with models instead of theories (or both) in Giere's view. This article raises important questions about the nature of models and theories, and about the connections between quantitative and qualitative representations in science, questions that will be with us for some time to come. It speaks to the problem of describing the knowledge structures of students and experts using the idea of hierarchies of structure, from qualitative to quantitative, and from concrete to abstract.

Parallels with model construction in scientists

The portrayal of learning as involving recurring model construction cycles in several of these articles (especially Gobert, Harrison and Treagust, Justi and Gilbert, and Buckley) parallels a similar development in cognitive studies of scientists. Much of the recent progress in history and philosophy of science can be seen as a struggle to move away from a simplistic view of how theories are formed in science as being either pure induction upward from observations or pure deduction downward from axioms followed by testing. Instead, we see movement toward a view that involves both top-down, bottom-up, and horizontal (e.g. analogical) processing in a cycle of conjecture and modification. Many modern scholars in the history of science and cognitive studies of science now view the process of how models are constructed in science as a cyclical process of hypothesis generation, rational and empirical testing, and modification or rejection. A major change in the basis for such views is that some of the recent work has been grounded in systematic studies of scientists rather than in abstract analyses of the nature of science. Theory formation and assessment cycles of this kind have been discussed by Gruber (1974), Nersessian (1984, 1992), Tweney (1985), Thagard (1992), Giere (1988), and Darden (1991) based on studies of scientists' records, and by Dunbar (1994) and Clement (1989) based on naturalistic and 'think-aloud' studies of expert scientists. This work means that there is now considerable empirical grounding for progressive model construction via revision in science. This is not to deny Kuhn's claim that major revolutionary shifts in theory are sometimes required; but even there the development of the new view is found to require many cycles of criticism and revision rather than being a single insight.

Using historical models in instruction

However, in this issue Justi and Gilbert present evidence that modern day textbooks are inconsistent and largely unclear about the nature of scientific models and their relation to scientific evidence and theory. Furthermore, they decry the misrepresentation of historical models in textbooks through inaccurate description, and this surely must be supported. They advocate the teaching of history and philosophy of science in teacher preparation courses so as to improve the level of discussion of models in the schools. This would seem to be an important step for developing the expertise/awareness needed to understand the interconnected roles of models, evidence and theory in learning.

The last question interacts with the articles in this issue: in the articles by Gobert and Buckley, intermediate models (partial models that are stepping stones between naive and expert models) are seen as valuable waypoints on a learning pathway between a naive and a more expert target model. Justi and Gilbert resonate with this theme when they advocate the use of particular historical models as intermediate models in the curriculum so that students can appreciate the ever changing nature of scientific models. Along these lines they document and lament the use of 'hybrid' models in textbooks (those combining two historical stages of modeling in a field). These, 'by their very nature, deny the possibility of history and philosophy of science [being] emphasized in the curriculum.'

However, to me this raises the question: if a hybrid intermediate model appears to be more readily understood than a historical model - should it be disallowed? And more generally, if a successful learning pathway through certain intermediate models is different than the historical pathway, but that pathway appears to be more natural and expedient for learning, which should be used? If the first pathway is not misrepresented as history, can it still convey the spirit of model improvement in science? The articles in this issue have given us the vocabulary to pose this question but they do not answer it. It may be a difficult trade off decision where it arises, but we are in a more advanced position now to even be able to contemplate the trade off, thanks to the articles in this issue.

Some important remaining cognitive research questions in conceptual change research

As I stated in the introduction, cognitive questions about the nature of learning have been complemented in recent years by other categories of questions pertaining to metacognition, social learning processes, and affective processes. I conclude that the articles in this issue, all support the idea that individual cognition, while not the only factor in learning, is a central determining feature of learning, and that we still have much to learn about it. In this section I will support this conclusion further by listing some controversies at the cognitive level that are as yet unresolved. Resolving these via an agreed upon theory could make a significant contribution to theories of conceptual change and instruction if we can make progress on them.

How can a theory of conceptual change support the design of instruction? Posner *et al.* (1982) proposed a set of conditions for conceptual change that are still relevant to this question. What has not been accomplished to date is the description of more detailed learning processes - the interior of the 'shell' that fulfills the conditions. Some ideas have been proposed to attempt to describe components of learning processes such as imagistic models, dissonance, analogies, and model sequences. However, researchers' current models of these processes often conflict, as illustrated by the following oppositions:

Imagistic Models

Understanding is primarily verbal *versus* Understanding is primarily imagistic (Monaghan and Clement 1999).

Dissonance

Teachers should avoid cognitive conflict as much as possible *versus* Cognitive dissonance is a primary motivator for conceptual change (Clement and Ramirez 1998).

Analogies

Single analogies are a powerful shortcut for organizing large bodies of conceptual material quickly *versus* Multiple analogies should be developed slowly and carefully and used to provide small image elements as building blocks within a larger process of model construction (Clement 1998).

Students should do the lion's share of the reasoning in using analogies for model building *versus* Teachers should carefully control the incorporation of analogies in instruction, by introducing, mapping, and pointing out limitations of an analogy.

Model sequences

Students learn understandings by being immersed in models that are as accurate and rich as possible (as is increasingly made possible by powerful computer simulations) *versus* students learn understandings best via a model evolution process by building on simplified, sparse, intermediate models that are only partially correct (White 1993, Steinberg and Clement 1997).

These conflicting views indicate that our field still lacks adequate cognitive theories of conceptual change, and requires intensive efforts in this area. Some of the above dichotomies will not have a single correct choice as an answer but rather the answer 'both' or 'it depends'. But we must pursue the questions: both in what mixture? or depends on what? We have only begun to satisfy the need to generate instructional principles for guiding the development of lessons and materials. We must expand the present partial theory of conceptual change to fill in the missing core of the present shell.

In conclusion, a goal that appears to be shared by most of the authors in this issue is to develop cognitive elements of a theory of conceptual change to the point where they can provide guidance to teachers in the form of instructional principles. They have succeeded here in moving us a step toward that goal. My view is that the cognitive piece of that theory will not be fully sufficient for this task, but that it will be essential to it.

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