Research Methodologies in Science Education: Mental Models and Cognition in Education

Julie C. Libarkin
Science Education Department, Harvard-Smithsonian Center for Astrophysics
60 Garden Street, MS-71, Cambridge MA 02138; jlibarki@cfa.harvard.edu

Meredith Beilfuss
Science Education Department, Indiana University
201 N. Rose Avenue, Suite 3002, Bloomington, IN 47405; mbeilfus@indiana.edu

Josepha P. Kurdziel
Department of Ecology & Evolutionary Biology, University of Michigan
830 N. University Ave., Kraus Natural Sciences Bldg., Ann Arbor, MI 48109-1048; josephak@umich.edu

It is summer break and Angela is preparing her syllabus for a new introductory level geology course. She has decided to approach the course by laying the foundations for the Theory of Plate Tectonics, and then teaching about a variety of geologic processes from a plate tectonics perspective. While designing this new course, Angela has been reading about cognition and mental models, and has begun thinking about how her students will understand the geological processes that she is planning to cover. Angela wonders: "How can I ensure that my students are learning the Theory of Plate Tectonics as geologists understand it? How do I ensure that students don't adopt mental models to help explain plate tectonics that are actually incorrect and confounding rather than explanatory?"

An active debate over the thought processes and cognition of individuals encountering new information, especially new scientific information, is an important component of science education discourse. Researchers are primarily interested in *whether* learners use models and *how* they use them. Do individuals carry conscious, internal cognitive models that represent their personal perception of the external world, or is interpretation of the external world an unconscious process? Are these models well-developed and stable (Smith et al., 1993), or are they constantly changing and not necessarily coherent (Greca and Moreira, 2000; Norman, 1983.)? In contrast, do learners spontaneously create explanations for new knowledge, and use these explanations to interpret phenomena (diSessa, 1993)?

Considering education from this perspective requires the blending of several different disciplines, including education, psychology, linguistics, philosophy, and cognitive science. As a consequence, specific terminology can have different meanings depending upon context. Here, we have adopted terms that are either most often used by the science education community or necessary for clarity. We have also chosen to synthesize a variety of theoretical perspectives, and identify four types of cognitive models (Figure 1):

1) *Naive mental models*, which are the intuitive or unconscious models used to interpret situations or knowledge;
2) *Unstable mental models,* which are typically considered to be inexact, incomplete, and used fluidly;
3) *Conceptual frameworks*, which in contrast to unstable mental models can be organized, stable, and often used mental models of the world; and
4) *Conceptual models*, which, following Greca and Moreira (2000), we will call those models adopted by groups as accurate, reasonable representations of natural phenomena.

The former three terms are generally used when discussing novice or naive cognition, while the well-developed theory of conceptual models implies a level of expertise with the phenomenon. Although some researchers may have adopted other terms for these elements, these four key divisions are generally recognized as important components of a discussion of cognition in education, regardless of the specific terminology used. With education, researchers hope to observe a direct relationship between conceptual models and an individual's mental model as a consequence of "quality" instruction.

CATEGORIES OF COGNITIVE MODESL

Cognitive psychologists would argue that people create cognitive models as a means for interpreting and navigating the world. Cognitive models are an individual's representation of a phenomenon, and are used to explain that phenomenon and predict outcomes. The exact nature of cognitive models is not known, and researchers disagree on the specific characteristics of a model. Certainly, models must be representative of physical phenomena, but the nature of that representation is still not known, especially in the geosciences.

Naive mental models - Although often considered to be distinct theoretical domains, it is useful to consider the naive problem representations of Larkin (1983) and the unconscious abstractions of diSessa (1983), called phenomenological primitives or p-prims, in a common category. Novice students use naive, intuitive approaches to solving problems, while experts build more detailed mental models that rest upon non-intuitive components, such as learned laws (Larkin, 1983). Similarly, p-prims are the spontaneously created basic building blocks of concepts or models, generated in response to new situations and knowledge (diSessa, 1983). Naive mental models differ from unstable mental models in that naive models are generally fragmented, unconnected pieces of knowledge and students are believed to be unaware of their underlying intuitions or p-prims.

COGNITIVE MODELS

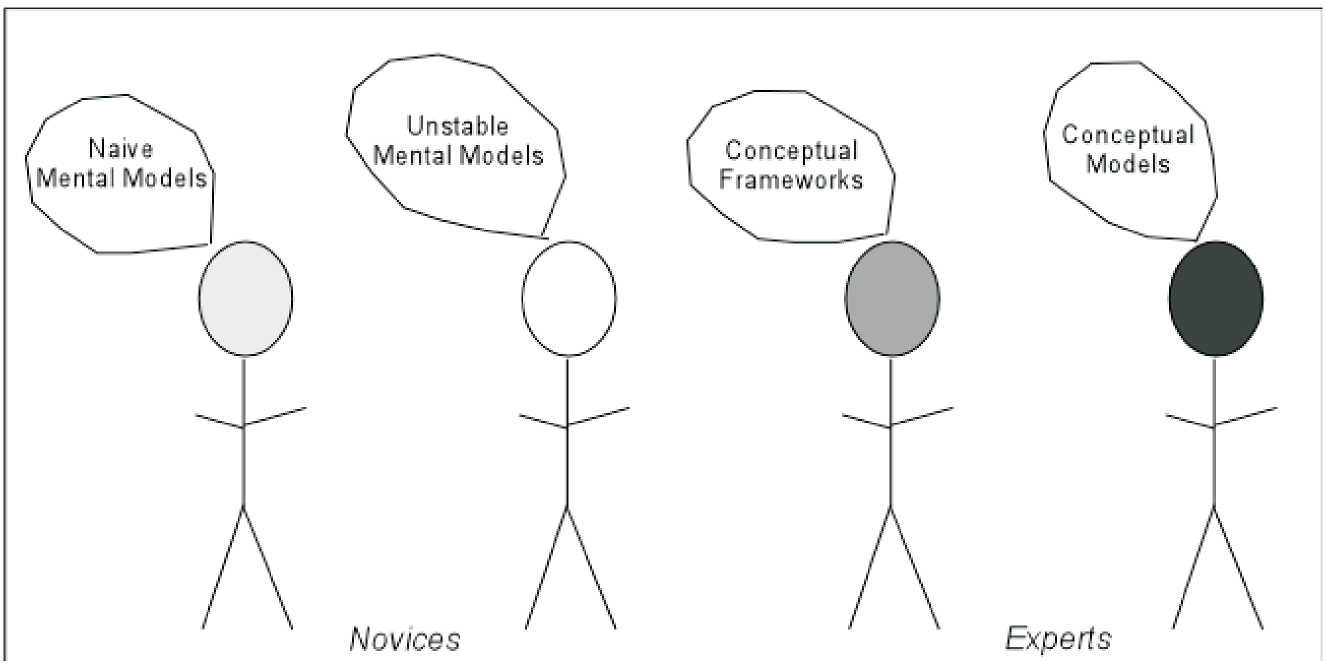


Figure 1. Four categories of cognitive models.

Unstable mental models and conceptual frameworks
It is useful to begin a discussion of models with conceptions (see Kurdziel and Libarkin, 2001 for a review) and conceptual frameworks. An individual's conceptions, ideas about what and/or why a phenomenon occurs, dictate how new knowledge is perceived and organized. The discussion of mental models and conceptual frameworks has two main schools of thought: those researchers who believe learners carry organized and stable models of the world (*conceptual frameworks*), and those who believe that mental models are unstable and inexact (*unstable mental models*). While both schools agree that mental models of similar phenomena vary widely from person to person, the digestion of new material by learners is highly dependent upon the type (e.g., stable or unstable) of mental model governing the students' thinking. On the one hand, learners with well-organized conceptual frameworks approach new situations from the context of these models, placing knowledge within the confines of the already established representation of the world. On the other hand, learners with inexact, incomplete, and even incoherent unstable mental models use new information as a means for adapting and modifying explanatory models. While stable mental models can certainly be modified as learners are faced with conflicting knowledge, unstable mental models are more easily modified, and current thought suggests that unstable models are continually being altered as new experiences are encountered and digested.

Conceptual models - In contrast to the internal, highly personal mental model, conceptual models are external and commonly accessible to anyone. Conceptual models are defined as representations of the world developed and used by expert groups to explain phenomena. Conceptual models are precise representations, including such things as mathematical formulae (e.g., Snell's Law), analogies (e.g., Solar System and Rutherford's atom...any geology analogies?), and physical models (e.g., laboratory aquifer models). Conceptual models are highly stable, and the acceptance of new theories and world-views by the scientific community can take a significant amount of time and effort; a classic example is the amount of time it took for Plate Tectonics to become a viable and accepted theory. A key component of this discussion of mental models and cognition, then, is the issue of stability.

STABILITY VERSUS INSTABILITY

How stable are people's ideas and explanations? Are solitary explanations of a phenomenon necessarily the rule, or can individuals carry multiple, contradictory explanations at the same time? How does a learner cognitively handle new knowledge; is information placed into 1) a stable, structured conceptual framework, 2) used to modify unstable mental models, 3) used as a basis for the unconscious creation and use of naive representations/p-prims, or 4) simply catalogued and memorized?

The nature of naive cognitive processes and mental models is a source of debate, particularly in the realm of stability. diSessa (1993) argues from one extreme that all knowledge is fragmented, and learning is simply the reorganization of fragmented knowledge into more intelligent order. The argument follows that acquisition of expertise occurs when p-prims are reorganized such that they are recalled in the most logical and illuminating order. P-prims, therefore, are the most unstable and fragmentary of all mental models or cognitive knowledge structures. Similarly, Larkin (1983) suggests that a novice's approach to problem solving may be entirely shaped by personal intuition. At the other extreme, Chi and Slotta (1993) argue that the acquisition of scientific expertise is a matter of building mental models, not reorganizing knowledge fragments. In their argument, these mental models are based on ontological principles, that is, information is categorized based upon specific characteristics of the phenomenon being interpreted. Similarly, other researchers (e.g., Ebenezer and Fraser, 2001) would argue that mental models are based on phenomenology, wherein people categorize experiences as a function of the interaction between themselves and the phenomenon.

ONTOLOGY

Ontology refers to the categorization of objects or phenomena with respect to their relevant properties. In cognition, this categorization is used to understand the mental models that an individual may be using to understand the physical world. Of particular interest to science education are two of the ontological categorizations delineated by Chi and others (1994): *Matter* and *Processes*. *Matter* refers to objects, such as fossils or epochs, while *Processes* refers to events and interactions, such as bioturbation or sediment transport. Chi et al. (1994) have suggested that a core difficulty in learning scientific concepts may arise when a learner assigns a concept to an incorrect ontological category. For instance, students may cognitively assign "heat" to the *Matter* category, since heat acts upon objects, without fully understanding that an action (a *Process*) is taking place. Additionally, some concepts may belong to either ontological category, depending upon context, and learners must learn to alternate between categories. As an example, tectonic plates are, in and of themselves, *Matter*, but often geologists using the term are evoking a range of processes that are better suited to a *Process* categorization.

PHENOMENOGRAPHY

Concepts and mental models do not exist in a vacuum. The way in which a person interprets an event or experiences new information is highly dependent upon the context of the situation. As a consequence it can be helpful to consider perceptions as a function of the relationship between the individual and the subject under scrutiny. Rather than simply describing the ideas that students have, phenomenographic analysis aims to define overarching themes that are found to exist across common subjects. For instance, in a study of students' ideas about energy and solution processes, Ebenezer and Fraser (2001) found that four descriptive categories were enough to describe the conceptions that students were bringing to a range of experiments. Uncovering the common thought processes applied to different content matter is a powerful method for understanding how students view the world around them.

ANTHROPOMORPHIC BEHAVIOR, PRE-DETERMINATION, AND OTHER EXPLANATIONS

Finally, it is useful to discuss another dimension of thought processes. A person's mental model reflects his/her belief system, acquired through observation, instruction, and cultural influences. Years of research indicate that people have a variety of ways of explaining phenomena, and some of these explanations are common across different disciplines. In particular, people tend to give human characteristics to inanimate objects (anthropomorphic behavior: "The volcano wants to erupt along the equator, so it does"), consider phenomena as inevitable and inexplicable (pre-determination: "The volcano erupts because that is what volcanoes do"), or vary explanations based upon the specific agent or population under consideration. For instance, a teleologic explanation, wherein the end result of a phenomenon is used to explain the phenomenon itself, such as: "Volcanoes occur along the equator because that's where it is hot". A variety of other types of explanations used by both novices and experts have been identified and are discussed by Southerland et al. (2001) and references therein.

EXAMPLE APPLICATION

We can exemplify how mental models are important in understanding how students learn through the research of students' views of the whole Earth, particularly in relation to space (e.g., Nussbaum, 1985 and Vosniadou and Brewer, 1992). In particular, ideas about the Earth's shape, its relationship to other cosmic bodies, and the relevance of these ideas to people can be interpreted from any of the theoretical perspectives described above. A range of thought experiments has been used to determine how students visualize the Earth and its relationship to space. For this example, we will focus on two well-studied topics: 1) the dominant characteristics of the Earth's shape; and 2) the nature of gravity on a spherical Earth.

NATIVE MENTAL MODELS

Students have demonstrated a number of intuitive or primitive ideas about the shape of the Earth during interviews. In our personal interactions with the Earth, we are rarely able to observe direct evidence of its spherical shape. Given this constant, and perhaps subconscious, experience, it is not unusual for students to believe that the Earth is flat (Table 1). This is an intuitive response, and students, even those in middle school, often demonstrate the embedded nature of this idea during interview probing (Nussbaum, 1985). Similarly, when asked to predict what would happen to a bottle, half-filled with water, when placed on the "opposite" side of the Earth, some students intuitively responded that the water would drain out of the bottle. The intuitive reason for this response, of course, is that water always flows out of open, upside-down containers.

UNSTABLE MENTAL MODELS

Students with a flat Earth view of the world may begin to modify cognitive models when faced with suggestions that the Earth is in fact a spheroid. Several interesting hybrid models, easily modified by students as they encounter the new information that the Earth is spherical, have been documented (Table 1). For instance,

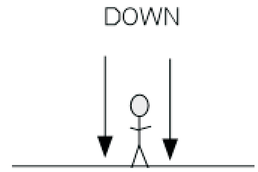
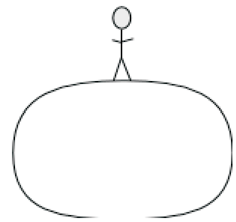
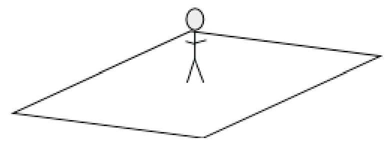
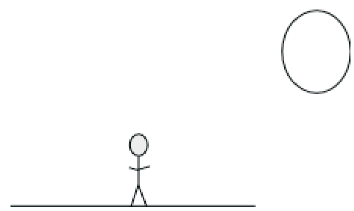
Cognitive Model	Description
Naive Mental Model: Flat Earth	
Unstable Mental Model: Flattened Spherical Earth	
Unstable Mental Model: Rectangular Earth	
Unstable Mental Model: Dual Earth	
Conceptual Framework: Gravity	Pictorial "down" is always gravitational down
Ontology: Matter	Flat Earth
Ontology: Matter and Process	Dual Earth

Table 1. Interpretations of Cognitive Models about the Earth's Shape and Gravity.

Nussbaum (1985) found that elementary and middle school students, when asked where people lived, would flatten the top and/or bottom of the circle drawn as a representation of a spherical Earth. In some cases, students went to the extreme of formulating a rectangular Earth model (Vosniadou and Brewer, 1992). People, students explained, lived on the flat parts, but nowhere else. Similarly, a dual Earth model has been documented (Nussbaum, 1985; Vosniadou and Brewer, 1992), wherein people living on a flat Earth can observe a second, spherical Earth in the sky. The flat Earth model was modified with exposure to the spherical Earth idea, suggesting the creation or modification of unstable mental models by students.

CONCEPTUAL FRAMEWORKS

Some students may have well-organized conceptual models governing their thinking about the Earth. Responses to problems with different contexts but similar structures were found to be remarkably consistent for some students, particularly with respect to gravity. For instance, a subset of students always indicated that "down" on a picture will dictate "gravitational down", whether the problem posed is water in a bottle turned upside down, a ball being thrown into the air, or how an object would fall through the center of the Earth (Nussbaum, 1985). This consistency in response is suggestive of a conceptual framework, in this case governed by the students' personal frame of reference.

ONTOLOGY

Student cognitive models about the Earth can also be interpreted ontologically (Table 1). For instance, most of the models used by children to explain the dichotomy between direct observation and learned knowledge are simple Matter states. On the other hand, the dual Earth model might be representative of both Matter and

Processes; both Earths are objects, but an interaction occurs between the observer and the spherical Earth. Some students also conceive of processes occurring between the two Earths.

PHENOMENOGRAPHY

Most of the research into student ideas about the shape of the Earth is phenomenographic in nature. Researchers have identified a few major categories that describe the ideas children have about Earth's shape. These include: Flat Earth, Spherical Earth, Flattened Sphere/Rectangle, Disc Earth, Hollow Earth, and Dual Earth (Table 1; Nussbaum, 1985; Vosniadou and Brewer, 1992, and references therein). These models are used consistently by students to explain a variety of phenomena and make predictions.

PREDETERMINATION AND EGOCENTRISM

Many students demonstrate predeterministic explanations of the Earth's shape. Students believe that the Earth is flat, disc-shaped, spherical, or hollow by caveat: This is the way a planet must be. Given this perspective, it may not be useful to engage in the common practice of conceptual change via challenge. Indeed, it may be impossible to challenge a student's notion about the Earth's shape through conflicting evidence; a planet's shape is not something to be understood, but simply accepted. Finally, it is interesting to point out that cognition about the Earth's shape may be related to egocentric notions about the Earth (Nussbaum, 1985). Certainly, the idea of a flat Earth is heavily embedded in an egocentric perspective, and an inability to look outside of your own personal frame of reference. While not surprising, it can be enlightening to consider student cognition from seemingly obvious vantage points. In the light of egocentrism, it seems significant that students may be unable to develop alternative cognitive models unless first taught how to think from multiple perspectives.

FUTURE DIRECTIONS

Current discussion of the link between cognition and research in science education generally focuses on the learner and the learner's cognitive state. A general assumption in most research involves using instruction to guide students towards a more scientific perspective, concept, model, or framework. However, very little research has been conducted to determine what defines "scientific", and in particular, how scientists themselves interpret the natural world (e.g., Nersessian, 1995). Geologists, in particular, have been underrepresented, and the actual meaning of a conceptual model to geologists needs to be explored. While the scientific community finds it useful to write down and teach stable, conceptual models, such as the Theory of Plate Tectonics, most geologists would agree that there is still a great deal that is unknown about this particular theory's parts. Indeed, several interesting questions suggest themselves when considering models adopted by groups and individuals:

1) What personal, internal models do geologists themselves use to understand plate tectonic processes, for instance? Are these models similar to the credo of Plate Tectonic Theory, and dissimilar to models held by students?

2) How do geologists modify their models of geologic processes in the face of emerging, conflicting data? How pliable are the mental models held by working scientists? Can the processes used by scientists to shift their own mental perspectives aid us as we attempt to teach students to think scientifically?

3) What are the salient characteristics of cognitive models used by both novices and experts to explain the Earth and geologic phenomenon? Which theoretical framework is most useful in interpreting these models: naive representat- ions/p-prims, unstable mental models, or conceptual frameworks? What is the best way to classify mental models: ontology, pheno- menology, or another categorization?

4) How does the use of mental models correlate to the use of physical or theoretical conceptual models in scientific practice? Are novices familiar with the components that are necessary for the creation of useful conceptual models (e.g., Justi and Gilbert (2002) and Treagust et al., 2002)? Once created, how do non-experts use conceptual models to understand the natural world?

5) Some scientists believe that a verbal description alone amounts to a type of mental model, especially when verbal cues or metaphors can be used to explain or predict phenomena (Lakoff and Johnson, 1983). Others, however, would argue that both verbal and visual representations that illustrate the relationships between phenomena and predictions are necessary components of cognitive models (Johnson-Laird, 1983; Pani, 1999). Although a significant component of the research being conducted is in the domain of cognition, our understanding of mental models in science, and especially in student understanding of geosciences, is too limited for this detailed view. Certainly, it would be useful to conduct further research to determine which type of model, verbal or visual, is most helpful for generating useful mental models of myriad geologic phenomena.

6) Finally, although it is clear that cognition is an important process for the field of teaching and learning, the impact of this research on classroom teaching is still unknown. How can geoscientists best use the research in mental models, the cognitive difference between experts and novices, and the research into model stability in the classroom? Does a "best practice" in teaching exist that can help students move from naive mental models to conceptual frameworks? How can we help students with naive internal models understand complex conceptual models?

REFERENCES

Chi, M.T., and Slotta, J.D., 1993, The ontological coherence of intuitive physics, Cognition and Instruction, v. 10, p. 249-260.

Chi, M.T.H., Slotta, J.D., and de Leeuw, N., 1994, From things to processes: A theory of conceptual change for learning science concepts, Learning and Instruction, v. 4, p. 27-43.

diSessa, A.A., 1993, Toward an epistemology of physics, Cognition and Instruction, v. 10, p. 105-225.

Ebenezer, J.V., and Fraser, D.M., 2001, First year chemical engineering students' conceptions of energy in solution processes, Phenomenographic categories for common knowledge construction: Science Education, v. 85, p. 509-535.

Greca, I.M., and Moreira, M.A., 2000, Mental models, conceptual models, and modelling, International Journal of Science Education, v. 22, p. 1-11.

Greca, I.M., and Moreira, M.A., 2001, Mental, physical, and mathematical models in the teaching and learning of physics, Science Education, v. 86, p. 106-121.

Kurdziel, J., and Libarkin, J.C., 2001, Research Methodologies in Science Education: Assessing Students' Alternative Conceptions, Journal of Geoscience Education, v. 49, p. 378-383.

Johnson-Laird, P., 1983, Mental models: Towards a cognitive science of language, inference, and consciousness, Cambridge, Harvard University Press.

Justi, R.S., and Gilbert, J.K., 2002, Modelling, teachers' views on the nature of modelling, and implications for the education of modellers, International Journal of Science Education, v. 24, p. 369-387.

Lakoff, G. and Johnson, M., 1980, Metaphors we live by: University of Chicago Press, Chicago.

Larkin, J., 1983, The role of problem representations in physics, in D. Gentner and A. Stevens, eds., Mental models, New Jersey, Lawrence Erlbaum Associates, Inc., p.

Nersessian, N.J., 1995, Should physicists preach what they practice? Constructive modeling in doing and learning physics, Science and Education, v.4, p.203-226.

Norman, D., 1983, Some observations on mental models, in D. Gentner and A. Stevens, eds., Mental models, New Jersey, Lawrence Erlbaum Associates, Inc., p.

Nussbaum, J., 1985, The Earth as a cosmic body, in R. Driver, E. Guesene, and A. Tiberghin, eds., Children's ideas in science, Milton Keynes, Open University Press, p. 170-192.

Pani, J., 1999, Descriptions of orientation and structure in perception and physical reasoning, in E. Winogard, R. Fivush, and W. Hurst, eds., Ecological approaches to cognition, Essays in honor of Ulric Neisser, New Jersey, Lawrence Erlbaum Associates, p.

Southerland, S.A., Abrams, E., Cummins, C.L., and Anzelmo, J., 2001, Understanding students' explanations of biological phenomena: Conceptual frameworks or p-prims?, Science Education, v. 85, p. 328-348.

Treagust, D.F., Chittleborough, G., and Mamiala, T.L., 2002, Students' understanding of the role of scientific models in learning science, International Journal of Science Education, v. 24, p. 357-368.

Ueno, N., 1993, Reconsidering p-prims theory from the viewpoint of situated cognition, Cognition and Instruction, v. 10, p. 239-248.

Vosniadou, S., and Brewer, W.F., 1992, Mental models of the Earth, A study of conceptual change in childhood: Cognitive psychology, v. 24, p. 535-585.

Libarkin and Beilfuss are supported by a National Science Foundation Assessment of Student Achievement in Undergraduate Education grant (DUE-0127765).