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The role of scaffolding student metacognition in developing mental models of complex, Earth and environmental systems

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"If you have built castles in the air, your work need not be lost; that is where they should be. Now put the foundation under them." Henry David Thoreau

Abstract

Students organize knowledge in Earth and environmental sciences and reason about environmental issues through manipulation of mental models. The nature of the Earth and environmental sciences, which are focused on the study of complex, dynamic systems, may present major difficulties to students in their development of authentic, accurate mental models of environmental systems. This project seeks to develop and assess IT-based learning environments that fosters student development of rich mental models of environmental systems through metacognitive scaffolding, manipulation of multiple representations, the development and testing of conceptual models based on available evidence, and exposure to authentic, complex and ill-constrained problems.

Issues in Tertiary Science Education

Calls for reform of science education, including Earth and environmental science, at the university and college level is not new. Passivity in students, often ascribed to the prevalent lecture format of science classes, the lack of dialogue with instructors, a focus on grades, and the need to develop thinking and reasoning in students, has been acknowledged for more than a century (Dutch, 1996; Howe, 1892; Smith, 1955). Concern about other problems including poor retention of scientific knowledge and lack of cognitive skill development in students, and the poor retention of students in science, especially those from underrepresented minorities, have also guided reform efforts. Though not directly tied to higher STEM education, the limited scientific literacy among the American public has also dismayed experts given the increasing technological nature of our society and the need for the public to understand important scientific and technological issues. What has seemed to change is the increasing sense of purpose among the American academy to engage college students in deep learning (Barr, 1995). This purpose is evident in a range of events including the increasing importance of broader impacts as an NSF criteria, evolving ideas concerning the nature of scholarship (Boyer, 1990), societal calls for increase accountability in the academy, and the need to develop scientists and engineers that can meet the challenges facing society in the 21st century (Good, 1994).

Recent reports on the state of university STEM education have focused on a number of potential problems that have clear implications for American society (National Research Council, 1996b). Many undergraduates do not receive enough education in STEM. Many STEM classes rely on textbooks heavy on "coverage" but weak on example, so that students are exposed to encyclopedias of fact without ever engaging in the process that is science. Even more frustrating is that fact that faculty who teach in the sciences, mathematics, and engineering often are engaged in exciting programs of inquiry, but undergraduates only rarely get to participate in these experiences. Poor pedagogy may account for the high drop-out rate of science majors and the low graduation rates of future science teachers for elementary and secondary school programs, who are essential if there is to be overall improvement in science education.

In a series of reports, national committees have focused on the state of STEM education in higher education institutions (George, 1996; Ireton, 1997a; Resnick, 1987; Stout, 1994; The Boyer Commission on Educating Undergraduates in the Research University, 1998). These reports are quite uniform in their critique of the current situation and recommendations. These recommendations focus on five general areas: content and curriculum; pedagogy and assessment; development of student skills in written and spoken communications, interpersonal skills, and problem solving and critical analysis; scientific literacy in citizens, and the potential of computer-aided instruction to support important educational goals.

The major objectives of science education reform has evolved to a focus on the development of educational practices and settings that develop learner's "habit of mind" (Duschl, 1997) to reason scientifically and engage in scientific inquiry (American Association for the Advancement of Science, 1989). This goal assumes students can learn the cognitive and manipulative methods of science exploration that generate data and evidence. It also assumes that students can use the reasoning and argumentation skills needed for theory development and evaluation that link evidence to explanations. A scientific habit of mind is an example of a **cognitive strand**, which we define as a set of interdependent cognitive and metacognitive skills and strategies (e.g. developing mental models, connecting multiple representations, visualization, using iterative processes, and critical thinking), that allow students to engage in scientific inquiry. Jim Minstrell has used a strand analogy to describe the nature of preconceptions in physics students and the role of effective instruction in developing understanding (Minstrell, 1989):

> *Students initial ideas about mechanics are like strands of yarn, some unconnected, some loosely interwoven. The act of instruction can be viewed as helping the students unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their ideas from and integrate them into conceptual beliefs like those of scientists.*

There are direct links between the education goals described above, the pedagogical practices that teach these skills, and the assessment techniques that test these skills. Empirical research and philosophical reasoning has led a large number of educational researchers to recommend that STEM education should evolve the dominant pedagogy used by instructors to forms which more strongly support these goals. STEM education should lessen its emphasis on didactic, lecture-based modes of instruction and increase its emphasis on learner-centered approaches, such as inquiry-based, problem-based learning, and cooperative learning, as well as an increase in the use of alternative assessment techniques including writing and oral presentations (George, 1996; Ireton, 1997a; Land, 1996; National Research Council, 1996a; Stout, 1994).

These reforms are particularly important for introductory courses, which are typically terminal science classes for many undergraduates (Stout, 1994). The perceived dullness or complexity of the material, a lack of concrete applications, and preconceptions among both students and instructors can make introductory science classes difficult for nonscience majors and can lead to lower retention rates of science majors (Delaughter, 1998). Introductory sciences are our best chance to increase scientific literacy of college students (Abd-El-Khalick, 2000; Laugksch, 1996; Miller, 1998). Scientific literacy is important for the health of a democracy in an increasingly technological society, where citizens are being asked to participate in important issues involving science and technology (Miller, 1998). Definitions of scientific literacy focus on the attainment of a level of understanding that allows citizens to appreciate the different sides of debates concerning technological or scientific issues (Miller, 1998). Recent large-scale surveys of European and American scientific literacy showed that approximately 20-30% of Americans are scientifically literate, based on their knowledge of vocabulary and process (Miller, 1998).

Mental Models and Earth & Environmental Science Education

Science education in Earth and environmental science (EES) issues has been cited as a potentially effective curriculum to address scientific literacy because of the social importance of environmental issues and the interdisciplinary nature of environmental science (Bazzaz, 1998; Bishop, 1998; Donahue, 1998; Hobson, 2001; Jenkins, 2003). In addressing scientific literacy issues, EES instruction often focuses on major environmental issues such as global climate change to foster development of critical thinking and environmental awareness in learners (Carpenter, 1999). The analysis of Earth & environmental issues as an educational context may also support intrinsic motivation to learn, as these issues are challenging, and educational outcomes and products can be applied locally and shared socially (Bransford, 1999).

There are three unique cognitive, epistological, and social characteristics of EES that may mediate student ability to reason about important environmental issues. While some of these characteristics are shared by other, more traditional scientific disciplines, taken together they form a unique set of characteristics that likely affect EES learning. The first major characteristic of EES is that environmental issues are value-laden and strongly socially constructed.

Secondly, the Earth and environmental sciences typically use a systems framework (Ireton, 1997b), highlighting the interdisciplinary nature of the discipline. The interdisciplinary nature of EES may have implications for knowledge transfer in students.

> *The objective of Earth System Science is to understand how the Earth is changing and the consequences for life on Earth with a focus on enabling prediction and mitigation of undesirable consequences. This requires an identification and description of how the Earth system is changing, the ability to identify and measure the primary forcings on the Earth system from both natural and human activities, knowledge of how the Earth system responds to changes in these forcings, identification of the consequences of these changes for human civilization, and finally, the ability to accurately predict future changes with sufficient advanced notice to mitigate the predicted effects.*
>
> *To achieve this level of knowledge and understanding a multidisciplinary approach to studying Earth as a system is needed. Such an approach involves studying the processes and interactions (cycles) among the atmosphere, hydrosphere, cryosphere, biosphere, and geosphere from a global to local point-of-view, and across the time scales (minutes to eons) in which these spheres interact. It requires the use of physical and chemical laws with mathematics to describe the physical, chemical and biological processes within each sphere and the interactions between the spheres. These descriptions are used along with observations from ground, airborne, waterborne, and spaceborne instruments to construct models through which complex interactions of the spheres are studied. It is through the understanding of these complex interactions that accurate, predictive models are developed.*
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> *Dr. Blanche Meeson, Assistant Director of Earth Sciences for Education and Outreach, Goddard Space Flight Center, May, 2000. (http://education.gsfc.nasa.gov/ESSSProject/ess_definition.html)*

This perspective developed in the 1980's in response to the growing understanding that large-scale environmental change required an integrated view of the mutual interactions between the biosphere, human society and the Earth. Earth system science focuses on the key processes that link the physical, chemical, biological and human dimensions of the Earth System, employing relevant problem solving methods and system modeling concepts. Scientific understanding of the functioning of environment systems is often built upon foundational research of more restricted questions following traditional reductionist approaches (Fig. 1).

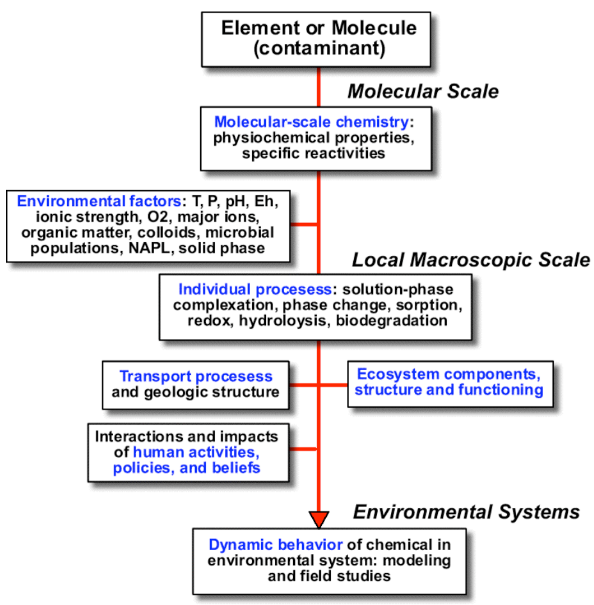

Figure 1. Modeling of environmental systems often builds upon fundamental knowledge developed through classic reductionist approaches, ultimately developing an understanding of dynamic system behavior (Schwarzenbach, 1993).

Finally, EES systems typically operate across a wide range of scales, and exhibit complex system dynamics. Environmental systems exhibit time lags, nonlinear feedbacks, have both deterministic and stochastic components that are essential to system stability, and are irreversible. It is also typical that there is a large amount of uncertainty concerning system characteristics. Complex system dynamics have been observed in species interaction in ecological systems (Brown, 2001), catastrophic shifts in ecosystems (Scheffer, 2001), stability of food webs (Neutel, 2002), and geologic systems (Valentine, 2002). The behavior and dynamics of environmental systems is often complex enough to make prediction of future behavior difficult (Doyle, 1998). Differences in the mental models of stakeholders concerning the properties of environmental systems has contributed to environmental conflict during ecosystem management (Hurley, 2003) and water resources management (Sneddon, 2003). People's mental models, when applied to risk perception, are also often ill-structured leading to incorrect perceptions of risk due to global warming (Kempton, 1991), radon (Bostrom, 1993), and electric fields (Morgan, 1990).

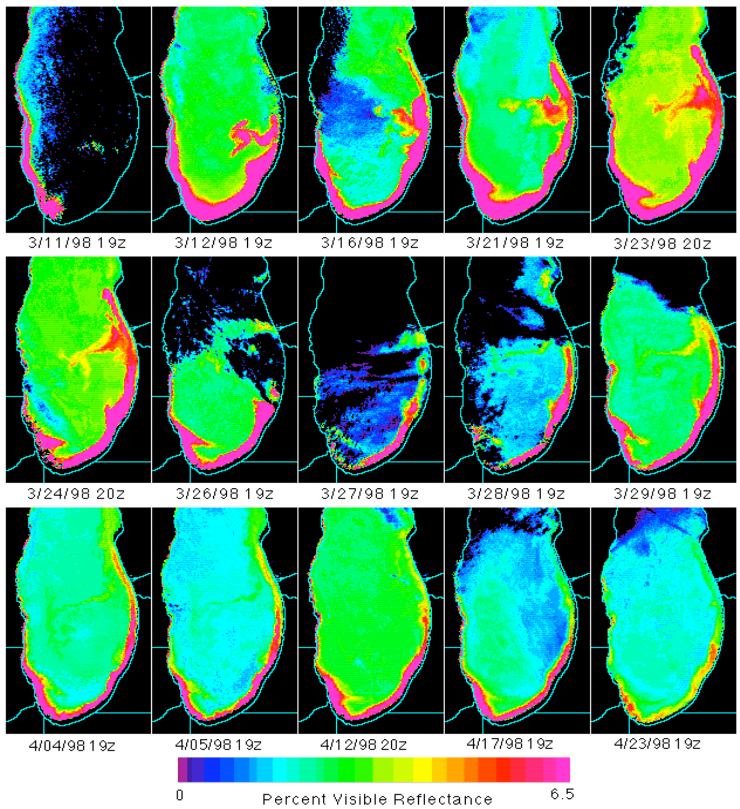

Figure 2. 1998 Environmental complexity: PCB-rich, suspended sediment plumes on Lake Michigan. Keith W. Bedford, Philip Chu and David Welsh, Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University

A mental model of a dynamic environmental system is defined as a relatively enduring and accessible, but limited internal representation of an external natural phenomenon (Doyle, 1998). The structure of the mental model maintains the perceived structure of the external system (Johnson-Laird, 1983). The theory of mental models has been extended to explain deductive reasoning (Johnson-Laird. P.N., 1993) and learning (Bransford, 1999). Though the research is limited, it is likely that many students have difficulty in understanding environmental systems of even modest complexity, predicting future system behavior in a variety of scenarios, and reasoning correctly about complex environmental issues (Ekborg, 2003; Forrester, 1994). Instructional sequences and learning environments that stress model-based teaching and learning may address these learning issues (Boulter, 2000). Modeling as a pedagogical tool involves cycles of model construction, exploration of model characteristics, applying the model to a specific problem, evaluation and revision, resembling authentic activities of scientists and mathematicians. Modeling emphasizes forms of knowledge representation and topics including visualization, data structures, and measurement and uncertainty. Model-based learning makes three contributions to science education (Gilbert, 2000). First, the formation and evaluation of mental models is central to developing an understanding of a scientific discipline. Second, the development and experimental testing of models supports authentic science inquiry-based learning. Finally, scientific models are major outcomes and products of scientific inquiry, and understanding the nature of science requires an understanding of these models within a philosophical, scientific and historical context.

Table 1. Classification of models

Model	**Description**
Mental Model	Personal cognitive representation formed alone or while interacting within a group
Expressed Model	A mental model placed in the public domain by an individual or group through the use of one or more modes of representation
Scientific Model	An expressed model developed through scientific inquiry and formal testing. The utility of scientific models is often judged on their ability to make empirically-supported predictions
Historical Model	Models whose utility has been agreed upon by a community in some historical context, but now has been superceded by other models

Table 2. Classification of representations

Modes of Representations	**Description**
Concrete	Physical models made of materials
Verbal	Descriptions composed of metaphors and analogies expressed in oral and written forms
Mathematical	Mathematical expressions
Visual	Graphical or pictorial forms in graphs or diagrams
Symbolic	A mixed mode representation

IT and Metacognitive Scaffolding

IT-based learning focused on the development and testing of models, in conjunction with experiential learning, can support the development of higher-order cognitive skills and competencies in learners including problem-solving, knowledge transfer, and decision making. IT-based learning should employ learner manipulation of complex data sets and physical models, the development and testing of conceptual models based on available evidence, and exposure to authentic, complex and ill-constrained problems. Because of these characteristics, the design and development of IT-based learning environments is directly supported by research activities conducted by university, government and industry and helps integrate research and education.

There is a need to enhance Earth & environmental science instruction at all levels through the further development and incorporation of effective and innovative IT-based learning materials in ways that build on the strengths of the Internet and distributed networks, and the availability of large environmental data sets. Given the individuality of instructional style and curricula, the development of IT-based instructional materials should be highly modular in nature to foster dissemination, where each module emphasizes the development of specific cognitive strands (e.g. connecting multiple representations, visualization, using iterative processes, critical thinking) and competencies in learners. In addition, further efforts needs to be placed on assessment of design and implementation strategies using authentic assessment methodologies.

IT-based learning has the potential to support important goals of the reform of higher STEM education. These goals include the reduction of didactic pedagogy, the development of higher-order skills and competencies, and an increased awareness of the nature of science in learners, and the retention of women and under-represented groups. Research on the effectiveness of IT-based learning in Earth and environmental science education is required because of the relatively limited amount of empirical research available specific to this discipline, the rapid development of Internet technologies, and the development of more robust cognitive models of learning and assessment methodologies.

The design and implementation of effective IT-based learning environments focused on inquiry and model-based learning requires strong links between cognitive science, instructional design, and assessment with feedback. *We hypothesize that the IT-based learning environments is most effective in supporting conceptual understanding of complex, natural systems when modules employ learner (i) manipulation of data and multiple representations, (ii) the development and testing of conceptual models based on available evidence, (iii) exposure to authentic, complex and ill-constrained problems, (iv) and contain explicit instruction in cognitive and metacognitive strategies.*

This project will seek to (i) design interactive, intelligent, database-driven IT-based environmental science modules with explicit instruction in cognitive and metacognitive strategies; (ii) implement the modules in introductory and advanced Earth science classes; and (iii) evaluate the efficacy of the modules to support the development of higher order skills in learners, increase student understanding of the nature of science, and increase ability of students to reason about environmental issues using rich, accurate mental models.

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