Use of Physical Models and Information Technology to Explore Student Difficulties in Developing Rich Mental Models of Complex Environmental Systems

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Abstract: Students organize scientific knowledge and reason about environmental issues by manipulating internally constructed mental models. The environmental sciences, which focus on the study of complex, dynamic systems, may present unique cognitive difficulties to students in their development of authentic, accurate mental models of these systems. This research seeks to develop and assess the coupling of information technology (IT)-based learning with physical models to foster undergraduate students' development of rich mental models of environmental systems. The components of the inquiry modules used in this study include manipulation of multiple representations, the development and testing of conceptual models based on available evidence, and exposure to authentic, complex and ill-constrained problems. Characterization of student cognition based on evaluations and factor analyses of learning products and expressions of student mental models suggest students' understanding of complex systems during inquiry-based learning is highly influenced by their cognitive skills and content knowledge. Imperfect conceptions and the lack of complexity and completeness in their representations of the studied systems were revealed in expressions of student mental models. This study illustrates the need to better understand student difficulties in solving complex environmental problems when using IT and physical models in order to implement the appropriate scaffolding to enhance undergraduate student learning in environmental science.

Gentner and Stevens (1983) maintain that mental models represent at any one time a human's understanding about the world and how it works. A mental model is defined as a relatively enduring and accessible, but limited, internal representation of an external natural phenomenon (Doyle & Ford, 1998). Research has indicated that students prefer simple mental model constructions (Harrison & Treagust, 1998; Coll & Treagust, 2003). Unfortunately, simplistic mental models do not accurately depict the complexity of the environmental sciences and instruction should focus on aiding the development of students' conceptual models. An instructional methodology that has been shown to increase students' depth of knowledge includes inquiry (NRC, 1996; Bransford, 1999). Authentic scientific inquiry provides students with the opportunity "to find solutions to real problems by asking and refining questions, designing and conducting investigations, gathering and analyzing information, making interpretations, drawing conclusions, and reporting findings" (Krajik et al., 2000). Development of student mental models should be an important learning outcome of authentic inquiry-based learning (IBL). Educational studies in a variety of scientific disciplines have aimed to design effective learning environments and instructional materials that scaffold student development of mental models that reflect complex natural phenomena (Pearsal et al., 1997; Gobert & Clement, 1999; Stoddart et al., 2000; Wu et al., 2001; Bao et al., 2002; She, 2004). However, little research assessing learning outcomes in undergraduate environmental science education has been conducted.

The central paradigm of the environmental sciences is the systems concept, where an environmental system is viewed as a "synergistic physical system of interrelated phenomena, processes and cycles" (Johnson et al., 2000). Though research is limited, it is likely many students have difficulty in understanding environmental systems of even modest complexity that would support the ability to predict future system behavior under a variety of scenarios, and reason correctly about complex environmental issues

(Forrester, 1994; Ekborg, 2003). There are four major characteristics of environmental systems that may present significant cognitive difficulty to students during development of rich mental models. First, most environmental issues and problems are interdisciplinary requiring student transfer of content knowledge from a variety of traditional academic fields; the knowledge in the fields must be situated into the context of environmental issues. Second, environmental systems encompass phenomena on a multitude of scales including the nano-, micro-, local-, regional- and global-scales. Third, most environmental systems are regulated through positive and negative feedbacks that result in complex system responses to perturbations. Finally, most environmental systems are characterized by spatial heterogeneity and temporal dynamics, often exhibiting chaotic behavior.

Eutrophication along the coastal margin, which serves as the scientific concept addressed in this research, is a good example of a dynamic process in a complex environmental system that is “made of many highly interconnected parts on many scales” (Vicsek, 2002). Eutrophication, a major research focus over the last decade, characterizes the impact of anthropogenic nutrient enrichments in coastal ecosystems (Cloern, 2001). It is the process in which excess nutrients (nitrogen and phosphorous) stimulate the growth of phytoplankton and indirectly the bacteria that feed upon the phytoplankton and other sources of particulate organic material (POM; e.g. phytoplankton, detritus, fecal pellets, etc.). Eutrophication ultimately causes hypoxia as the bacterial metabolism depletes oxygen levels in the water column (Oviatt et al., 1986; Nixon, 1992). Hypoxia, traditionally defined when dissolved oxygen is < 2 mg O_2 L^{-1} in the water column, has been observed in at least 44 reported places in the world

(Morehead et. al., 2002). It commonly occurs in aquatic, marine, and riverine systems that are stressed by anthropogenic nutrient inputs which are controlled by land-use patterns, production and application of fertilizers, discharge of human waste, animal production, and combustion of fossil fuels (Nixon, 1995). Eutrophication and hypoxia have been observed in Chesapeake Bay (Sagasti et al., 2001), the Northern Gulf of Mexico (Harper et al., 1981; Turner & Rabalais, 1991; Rabalais et al., 1994), the Baltic Sea (Gamenick et al., 1996), the Black Sea (Tolmazin, 1985), and the Adriatic Sea (Justic et al., 1987).

Instruction can enhance students' abilities to connect their mental models and the reality of real world phenomena with mediation through which often both include digital and physical expressions of environmental systems. Information technology (IT)-based representations, including simulations of environmental systems, distributed networks of scientific and social science knowledge, visualization of complex data sets which builds on the strong human ability to comprehend patterns, and the extension of human senses by collecting data and observations at spatial and temporal scales, are particularly useful. Instructional sequences and learning environments that stress the use of multiple representations, the development of student mental models, and inquiry-based learning (IBL) can enhance students' understanding of the nature of science and the development of cognitive and metacognitive skills such as higher-order thinking, communication, knowledge transfer and decision-making skills (Boulter & Gilbert, 2000; Author, 2003). Modeling as a pedagogical tool involves cycles of model construction, exploration of model characteristics, application of the model to a specific problem, evaluation and revision; thus, resembling authentic activities of scientists (Buckley & Boulter, 2000).

Successful applications of physical models in the collegiate setting have been recorded and results indicate that students can develop rich understandings of science (Barab et al., 2000). The use of multiple representations are likely fundamental in conducting IBL within the environmental science classroom because they promote the support to solve student learning difficulties and provide the best solution to accurately represent the studied systems.

Not only do environmental systems involve extreme complexity, but student learning of science within the constructs of a social environment (e.g. a classroom) is also complex (Davis & Simmt, 2003). In this research the IT and inquiry based learning added even further complexity and ambiguity in determining student learning. In order to assess the many variables that may influence students' ability to enhance their mental models through using multiple representations, this study has utilized the method of factor analysis. Factor analysis can be useful for classroom research in that it reduces the number of otherwise discrete, observed measures to a smaller number of underlying conceptual variables through a process of clustering alike variables. Additionally, factor analysis allows the research to make links from the observed measures to the unobservable ones. Previous work in science education has utilized this approach to interpret secondary students' environmental attitudes (Worsley & Skrzypiec, 1998), student's perceptions of science (Bezzi, 1999), and students' science achievement (Wang & Staver, 1998).

This pilot study attempts to evaluate the development of students' mental models (i.e. their development of higher order thinking skills, their understanding of the nature of science, and their imperfect conceptions of the studied science) through instruction that is interactive, database-driven, and IT-rich. We hypothesize that instruction that guides students' exploration of authentic scientific questions through their manipulation of multiple representations (coupling IT and physical models), will reveal student difficulties in understanding, using, and developing their mental models of environmental systems.

Experimental Design

Participants

The upper-level environmental geology course included 15 (6 male, 9 female) juniors and seniors at Texas A&M University. Membership of the class was predominantly geology majors (93.3%) with diverse course backgrounds/content knowledge (Table 1). Noteworthy in their backgrounds is their limited prior factual knowledge in the environmental sciences, in that only one of the learners had taken the course. Pre-assessment surveys revealed that the students were generally unfamiliar with many of the concepts to be covered in the course, including core concepts such as "coastal margin" and "Earth system science." Students' descriptions of their knowledge about the applications of IT in solving research questions revealed examples related to the construction of data graphs or web-searches. None incorporated the use of modeling tools such as geographical information systems (GIS) or the use of reference material such as on-line journals into their descriptions, which were tools that would be used throughout the course. In the same survey, 100% of the students expressed a desire to continue on to graduate school, several of whom wished to continue specifically in the environmental sciences, and many (87%) described themselves as independent learners. When asked to rank the most important learning characteristics that they should receive from the course, they listed in decreasing order: (1) to develop skills in using material, tools, and technology in this field; (2) to learn terms and facts of this subject; (3) to develop a commitment to accurate work; (4) to learn concepts and theories of subject; (5) and to develop analytical skills.

Context

The course was designed to facilitate IBL, specifically student-guided inquiry, where all laboratory projects were geared around the use of inquiry as an instructional model. The IBL setting was based on NRC (1996) and Krajick et al. (2000) definitions of inquiry. Inquiry is the diverse way scientists study the natural world and pose explanations based on evidence derived from their work - it requires asking and refining questions, designing and conducting investigations, gathering and analyzing data, making interpretations and conclusions, and reporting findings; it promotes the development, transformation, and representation of ideas; and it emphasizes depth and not breadth.

In the IBL setting of the course, students were encouraged to work in groups to complete assignments, to explore outside resources aside from their given text, and to use the scientific method during problem solving. Module topics included eutrophication; water quality; sedimentary biogeochemistry; estuarine and freshwater carbon diagenesis; nutrient sources, sinks, cycles, spatial and temporal trends; and land-use impacts on watersheds. The IT tools used by students included Excel©, PowerPoint©, ESRI ArcView© GIS, and the World Wide Web. Classroom tutorials during lab exercises provided the scaffolding for the use of the technologies. PowerPoint© lectures were used in association with laboratory exercises when needed, as well as background readings and one-on-one small group help through Socratic inquiry methods.

Instructional sequence

Four IBL modules consisted of three major topics where multiple representations were utilized during student activities (Table 2); (1) exploration of sediment biogeochemistry through use of a physical model (2) exploration of large-scale spatial and temporal water quality trends and land-use through data visualization (3) exploration of eutrophication through animation construction. In the first module, the students used the physical model; in the next two, students engaged in IT-based learning; and in the final lab they delivered group presentations.

The physical model included the building of a Winogradsky column, which is a clear tube of sediment that is allowed to go anaerobic through the utlization of O_2 during microbial respiration (Deacon, 2004). Temporal visual changes are direct evidence of these processes, including the formation or loss of minerals such as pyrite, or the development of visible colonies of variably colored microorganisms. Students choose among several variables, including addition of organic substrate (molasses or oil), aeration, nutrients, or sediment type (marine or freshwater sediments), to evaluate the impact of these variables on microbial respiration over a three-week time span. The physical model represented small-scale biogeochemical processes that occur in sediments of both estuarine and wetland environments. The IT exercises incorporated the use of geographical information systems (GIS) and Excel© to study large-scale spatial contamination in two Texas estuaries and the South Platte, CO watershed through access to large data sets. In these modules, students chose the data they deemed important to analyze according to their hypothesis about the system. Further, students were asked to design their conceptual models of the eutrophication process as an animation and present it to the class. The learning products that were developed from the implemented laboratories included three written reports (incorporating the technologies of digital photographs, Excel© plots, and ESRI ArcGIS© maps) and a PowerPoint© animation (Table 2). The product development allowed for assessment of student mental models, exposing any imperfect conceptions and/or inabilities to incorporate observed data and trends into their conceptual models.

Instrumentation & Reliability

Development of a rubric enabled quantitative analysis of student's work through a pre-constructed set of standards and learning goals, where a point system was designed to assess student performance. The rubric acted as the instrument to assess learner knowledge in relation to the cognitive skills needed to perform the inquiry tasks. Design of the assessment instrument was guided by our interpretation of the cognitive skills an expert scientist would use to solve authentic problems. Major rubric categories were defined based upon cognitive skills summarized Chin and Malhotra (2002) including (i) knowledge building, (ii) question generating, (iii) research design, (iv) reasoning, (v) explanation of results, (vi) interpretation of research reports, (vii) interpretation of observations, (viii) summarizing findings (Table 3). Based on these cognitive processes, ten total categories of cognition were determined as criteria for the rubric, including (i) content knowledge, (ii) construction of a hypothesis, (iii) experimental design, (iv) ability to think critically, (v) inclusion of references (vi) and standards, (vii) ability to collect and report data (viii) writing organization, (ix) creativity, and (x) inclusion of essential components to communicate research findings (Table 3).

Reliability of the instrument was performed by a team of five graduate students serving as external evaluators. The evaluators were not involved in the implementation of the current research but enrolled in the departments of Teaching, Learning & Culture (TLAC) and Geology & Geophysics at Texas A&M University. Three sample student reports of varying quality were randomly selected from a report database where each evaluator graded all three. Reliability was assessed by calculating internal consistency values using Cronbach's alpha using the statistical package SPSS. Table 4 illustrates the resulting inter-rater reliability, where all rubric categories gave at least 70% agreement among evaluators and each report gave at least 74% total reliability. When considering that in exploratory research a modest reliability of 0.50 to 0.60 is acceptable (Ravid, 1994, p. 292), the final instrument showed moderate reliability in differentiating students' products (Cronbach α: 0.74 – 0.89). Therefore, all student products were evaluated based on this quantification method.

Factor Analysis

Factor analysis, a data reduction technique for multivariate datasets, was used to identify the most important variables impacting student learning within this specialized IBL setting. Factor analysis was used to cluster related variables indicative of learning, including rubric scores within each measured category and between inquiry projects, final grades on inquiry-projects, final course grades, exam grades, and student grade point ratios (GPR). The variables were extracted through the use of a principal component extraction with Varimax rotation and Kaiser normalization. The factor loadings represent the relative importance of each variable within each principal component. Factor analysis reduced the multivariate dataset into linear combinations of the most relevant variables to facilitate interpretations and enable the recognition of differences and similarities between variables in the dataset. Groups of variables that have loadings of the same sign (i.e. positive or negative) on a factor component describe similar anomalies or patterns in the data set, while variables with opposite signs do not. The magnitude of the individual loadings was also considered in distinguishing results.

Results

The factor analysis produced a total of nineteen principal components (see Figure 1 displaying the first 10 factors). Five components achieved an eigenvalue > 1 and represented 83.2% of the variance (Table 5). Table 6 displays the factor loadings of Components 1-5 resulting from a Varimax rotation. Component 1 represented the majority of the dataset (10 data points), where Components 2 -5 represented eight of the nine remaining data points (Table 6). Figure 2 illustrates Components 1 -3 where variables cluster into various categories. Components 1 -2 were interpreted to represent the students' cognition where Component 3 represented their content knowledge. The cognition cluster was divided into several subcategories where Component 1 included reasoning skills and critical thinking skills and Components 1 & 2 represented cognitive load difficulties. The content knowledge cluster represented by Component 3 also divided further into subcategories including understanding of scale and characteristics and behaviors of systems.

Student performance on inquiry modules was also characterized through analysis of the rubric scores where student average scores were evaluated in each rubric category and each module (Table 7). Results indicate that the IT modules were more difficult endeavors for students as compared to the physical model and animation exercises. This may have been due to the cognitive load issues. Despite efforts to properly scaffold the students, IT inquiry modules may have overwhelmed students because of the convergence of the multiple skills required to perform the project tasks. Further insight to student cognitive processes is noted, where students generally scored lower on the inclusion of a hypothesis (0.86) and referral to references/standards (0.17) than on the other rubric categories (> 1.21). Therefore their understanding of the scientific inquiry methodology may have not strongly included these components; particularly when students' cognitive load was high, they may have often disregarded these scientific components of inquiry. Student average scores on exams (mid-term = 65.0% and final = 61.5%), and final course grades (71.6%) also reflect inadequate content knowledge achievements.

Finally, several imperfect conceptions were revealed during student mental model development, including issues of scale, application of factual knowledge and reasoning. The use of the term "imperfect conception" was preferred over the term "misconception" in this study because "misconception" implies a negative, incorrect student response, whereas "imperfect conception" implies a naive conception that is only partially correct in the examined situation but could be entirely correct given a different scenario. The definition of an imperfect conception in this work includes reasoning, thinking, and using terms that may be correct when applied to other cases, but in the phenomena under study it was either inappropriate or misapplied. Examples of typical imperfect conceptions in this work included student response scenarios as found in Table 8. Student A's response was an imperfect conception because "molecules" are not bigger than "cells" therefore their mental model did not account for scale. Student B's and student C's responses inappropriately used the course terminology in their explanation of phenomena. The definition of a chemically "reduced" environment cannot contain oxygen yet "aerobic processes" utilize oxygen to proceed, so student B's statement contradicted itself. Student C's statement was also contradictory because the formation of "pyrite" must occur in oxygen free environments, therefore "oxygen" can not be "readily available" during its formation. Student D's statement illustrated very simplistic logic used in reasoning that did not reflect the complexity of the system under study. The student reasoned that the newly formed "black material" may have been "bacteria" based upon a limited understanding of links between biotic (bacterial respiration) and abiotic (iron reduction and the precipitation of black or framboidal pyrite) processes, an important characteristic of most environmental & Earth systems. The above imperfect conceptions reiterate the student difficulties as found in the factor analysis where difficulties in reasoning, content, and scale were also indicated.

Even though such imperfect conceptions may be frustrating for the instructor, it should be noted that without involving students in such inquiry-based tasks and allowing them to express their mental models, these imperfect conceptions may never come to the attention of the instructor or the student. Further evaluation of student mental models revealed another apparent student difficulty- the mental models did not reflect the complexity of the environmental system under study. This may be largely attributed to student difficulties in reasoning, content knowledge, and ability to understand differences in scale and system behavior.

Discussion

Previous research has shown that the richness of a learner's mental model directly influences his/her quality of task performance in that domain (Barker et al., 1998). Several science domains have evaluated undergraduate student difficulties in their development of rich mental models. Research has been conducted in the physics classroom, where student strengths and weaknesses in understanding magnetic field theory have been identified (Guisasola et al., 2004). Results indicate that students' often did not exhibit meaningful understanding, with students often creating non-scientific conceptual models of explanation. Further, students' imperfect conceptions in electrochemistry have been studied as well (Sanger & Greenbowe, 1997). Findings suggest that students capable of solving quantitative examination problems often lack an understanding of the underlying concepts. Although this type of research is common in traditional science domains (i.e. physics, chemistry, and geology), little similar research has been conducted in undergraduate environmental science courses. Environmental systems are innately complex in nature and may prove difficult for student development of accurate mental models. Thus, questions of interest in environmental science education research include "How do we authentically represent environmental systems to enhance student mental model development in instructional contexts?", and "What are the student difficulties associated with developing rich mental models of complex environmental systems?"

This pilot study has attempted to address these questions by implementing, designing and assessing instructional modules in an undergraduate environmental science classroom, where the use of multiple representations (IT and physical models) were used to accurately depict the complexities of environmental systems to students. The current work enabled the identification of many potential areas of student difficulties in the environmental sciences through the use of factor analysis. Students had difficulty developing accurate and complex mental models of environmental systems even while using IT and model-based learning in this pilot study as seen in students' overall performance. Factor analysis identified data clusters which were interpreted to represent students' content knowledge and the cognitive skills of reasoning, critical thinking, cognitive load difficulties, understanding scale, and understanding system behaviors. These categories provided insight to areas of probable student limitations in the formation of accurate and complex mental models of environmental systems. Data also suggested that the students' understanding of the scientific method of inquiry was limited and that key components were weakly applied or were altogether missing from student products. Further, student imperfect conceptions revealed in the mental model evidence illustrated that content knowledge was essential to forming logical scientific arguments. This also may have been an indicator that sufficient content knowledge was lacking, and further development of instructional scaffolding was needed. Although previous research indicates that IBL is an approach worth investigating in teaching and learning science (Krajcik et al., 2000), it cannot be forgotten that sufficient content knowledge needs to be gained by the student in order to have the essential core knowledge to make reasonable/logical choices and to proceed with a complex thinking process (Jonassen, 1999). Other noted student difficulties were identified in the IT inquiry modules, which may have overwhelmed students because of the associated cognitive load and convergence of multiple skills needed to perform the desired task. Therefore, students may have easily excluded some components of scientific inquiry when faced with IT modules. Although the current research results may have highlighted some student difficulties with IT, it is important to note that the IT experience allowed students to visualize the large-scale societal/geological impacts on the environment (i.e. ESRI ArcGIS© software); these issues can often be complex and difficult to decipher, yet no other instructional tool in the environmental sciences has allowed students to experience this first hand.

The results of this pilot study indicated the need for further research in the teaching and learning of IBL modules using IT and physical models and their impact on students' mental model development in environmental science education. Steps to enhance mental model development of complex environmental systems among university students will include refining the scaffolding, support, and pedagogical content knowledge the teacher brings to the learning situation (Barnett and Hodson, 2001; Driel et al., 2001). However, the identification of student difficulties was a useful preliminary assessment in order to determine the needed pedagogical improvements. The use of IT has been previously practiced in university-level science curricula; however, it has not been commonly applied within IBL environments or with the appropriate scaffolding to achieve enhanced student learning, especially for the complex and dynamic field of environmental science. To accomplish this task, further inquiry implementations coupling IT-based learning and physical models as learning tools are planned for a variety of undergraduate environmental science courses. These courses will focus on replicating the learning goals in this research, where student development of rich mental models of complex system science will be a driving motivation. Furthermore, the analysis of environmental issues as an educational context may also support intrinsic motivation to learn in students, as these issues are challenging, and educational outcomes and products can be applied locally and shared socially (Bransford, 1999).

Conclusions

The described study involved the implementation of IBL in an upper-level undergraduate environmental geology course at Texas A&M University. The research sought to develop and assess IBL environments that would promote student development of accurate and complex mental models of environmental systems through performance on implemented modules, where exposure to multiple representations to solve authentic, complex and ill-constrained problems occurred. The implemented pedagogy of coupling both IT-based and physical model representations provided an opportunity for the "hands-on" approach to learning both the large and small-scale processes that occur in environmental science. Assessment of students' mental model development and performance on IBL modules provided insight to student learning difficulties, imperfect conceptions, and constraints when exposed to complex environmental systems. Results indicated that students' cognitive skills are not adequately developed and that possible undeveloped cognitive processes (i.e. critical thinking, reasoning, linking large/small scales and understanding system behavior) highly influences accurate mental model development. It has become apparent that more research is needed in the teaching and learning of environmental science, where emphasis on model-based learning and IT use is necessary in understanding the cognitive needs of students when exploring such dynamic and complex systems. Appropriate student scaffolding and implementation of pedagogical content knowledge by instructors at the university level need to be developed in order to address these undergraduate learning needs, particularly within the context of IBL modules.

Implications

Issues surrounding cognitive difficulties of complex earth and environmental systems are not limited to students in formal educational environments. Recent efforts to develop innovative methods for environmental management and risk assessment have focused on adaptive management processes that involve a wide range of stakeholders, including experts, policy makers and citizens, in the decision process (NRC, 1999; Renn, 1999; Allen et al., 2001; McDaniels & Gregory, 2004). Environmental management requires knowledge about the environmental problem, decision alternatives and consequences, uncertainties, and trade-offs (McDaniels & Gregory, 2004). Adaptive management relies on a policy-analytic decision process involving stakeholders in an iterative process where learning is explicitly incorporated into the decision process (McDaniels & Gregory, 2004).

Poor mental models of complex environmental systems have led stakeholders to poor environmental decisions and risk assessments. Variations in stakeholder mental models of environmental systems have contributed to environmental conflict during ecosystem management (Hurley et al., 2003) and water resources management (Sneddon et al., 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 et al., 1991), radon (Bostrom et al., 1993), and electric fields (Morgan et al., 1990). It is likely that some of our understanding about how students learn about complex environmental systems in formal educational settings can be applied to develop an understanding of stakeholder learning of the same systems under more informal conditions, with an objective of improving environmental management and decision processes. Research, though, would need to be conducted on the impact of differences in the learning environments and learners, and design of appropriate scaffolding techniques, particularly those that employ advanced information technologies.

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Table 1
Student course backgrounds

Course Name	N Students	Percent (%) of students that completed course
Introductory Courses		
Chemistry 101	14	93.3
Geology 101	14	93.3
Environmental Science	2	13.3
Advanced Geoscience Majors Courses		
Sedimentology and Stratigraphy	11	73.3
Geochemistry	5	33.3
Advanced Geoscience Elective Courses		
Hydrology or Hydrogeology	6	40.0
Geographical Information Systems	1	13.3
Geomorphology	1	13.3

Table 2

Implemented laboratory topics, studied systems, represented scales, utilized modes of representation and the produced student learning products

Topic	**System**	**Scale**	**Representations**	**Learning Products**
Sediment Biogeochemistry	Wetland & Estuarine Sediments	Local Scale (m)	Physical Model: Winogradsky Columns	Written Reports
Water Quality	Texas Coastal Margins	Spatial Variability over Regional Scales (km)	Visualization of Complex Data (IT: Excel, GIS, Internet)	Written Reports
Land Use & Water Quality	South Platte, CO	Spatial Variability over Regional Scales (km)	Visualization of Complex Data (IT: Excel, GIS, Internet)	Written Reports
Eutrophication	Texas Coastal Margins	Temporal Variability over Seasonal Scales (months)	Animation of System Dynamics	Presentation of Computer Animation

Table 3

Rubric assessment criteria as according to the cognitive processes associated with authentic scientific inquiry (modified from Chin and Malhotra, 2002)

Cognitive Process	**Authentic Inquiry**	**Rubric Assessment Criteria**	**Rubric Category**
Build knowledge	Scientists improve their knowledge base overtime	Does the student correctly apply the course content material?	Content knowledge
Generate research questions	Scientists generate their own research questions	Does the student state a testable hypothesis?	Hypothesis
Design studies	Scientists select variables, invent procedures, employ controls to address questions of interest.	Does the student employ an experimental design that is appropriate for the research question?	Experimental design
Reason	Scientists employ multiple forms of argument.	Does the student use scientific logic in determining possibilities for deviation from original expectations?	Critical thinking
Explain results	Observations are made, data is transformed into other data formats, observations are related to research questions.	Does the student link evidence to explanation? Does the student think critically in their explanations?	Critical thinking
Interpret research reports	Scientists study other scientists' research reports.	Are references to other case studies, literature, and standards made?	References/ Standards
Interpret observations	Scientists employ elaborate techniques to guard against bias.	Does student include collected data (graphs/ tables/ figures) and state the assumptions of their analysis?	Data collections
Summarize findings	Scientists make written reports, manuscripts, and presentations of their findings.	Does the student product (i.e. report) exhibit organization, coherence, creativity, and all of the components typical of scientific publications?	Organization/ Creativity/ Scientific components

Table 4

Inter-rater reliability of the rubric – ability for evaluators (n=5) to score similarly on rubrics where scores are assigned ratings of 0, 1, or 2.

Rubric Category	**% Agreement of Evaluators (n=5)**			**Avg. %**
	Report 1	**Report 2**	**Report 3**	
Content Knowledge	80	60	60	**70**
Critical Thinking	60	60	80	**70**
Scientific Components	80	80	80	**80**
Data Collection	80	60	60	**70**
Hypothesis	80	80	60	**70**
References	80	100	100	**90**
Standards	60	60	100	**70**
Experimental Design	100	80	60	**80**
Creativity	80	80	60	**70**
Organization/ Coherence	100	60	60	**70**
Cronbach's α	**0.74**	**0.87**	**0.89**	

Table 5

Component Eigenvalues before and after the five factor Varimax rotation.

Component	**Initial Eigenvalues**			**Final Eigenvalues**		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	8.327	43.827	43.827	6.461	34.003	34.003
2	2.997	15.775	59.601	2.754	14.497	48.500
3	1.907	10.037	69.638	2.637	13.880	62.380
4	1.417	7.458	77.097	2.031	10.687	73.067
5	1.164	6.128	83.227	1.930	10.158	83.224
6	0.896	4.714	87.938			
7	0.686	3.613	91.551			
8	0.454	2.074	93.942			
9	0.394	1.815	96.016			
10	0.345	1.048	97.831			

Table 6

Principal component model parameters for five factors (components)

		Components				
		C-1	**C-2**	**C-3**	**C-4**	**C-5**
Factor Analysis Loadings Rotated						
Cognition (Cognitive Load, Reasoning & Critical Thinking)	Org	0.85	0.19	0.19	0.01	0.09
	Create	0.83	0.49	0.08	0.14	0.12
	IT.SP	0.80	0.21	-0.04	0.15	0.38
	Grade	0.80	-0.13	0.43	0.05	0.05
	Design	0.80	-0.24	0.03	0.12	0.07
	Con	0.74	0.14	0.28	0.48	0.20
	Data	0.72	0.12	0.54	0.13	0.04
	Think	0.72	-0.12	0.35	0.52	0.19
	Anim	0.67	-0.33	0.12	0.13	-0.17
	Comp	0.59	0.24	0.33	0.29	0.40
Content Knowledge (Understanding Scales/Systems)	Stds	-0.11	0.59	-0.39	0.66	0.01
	Refs	0.31	0.57	0.30	0.01	-0.06
	GPR	0.24	-0.08	0.91	0.00	0.02
	Physical	0.15	0.17	0.53	0.02	0.55
	Midterm	0.04	-0.62	0.30	-0.11	-0.57
	Final	0.17	-0.16	-0.04	0.58	-0.14
	IT.Coastal	0.39	0.10	0.36	0.56	0.05
	Hypo	0.23	-0.05	0.07	-0.15	0.78
	Courses	0.08	-0.88	-0.01	0.11	-0.09

Extraction method: Principal component analysis
Rotation method: Varimax with Kaiser normalization

Table 7

Average student scores (0=low, 2=high) for rubric categories for each IBL module along with student mid-term exam, final exam, course grade, and GPR averages.

Rubric Category	**Rubric Abbreviation**	**Physical Model Avg. Score**	**Animation Avg. Score**	**IT- Texas Coastal Margins Avg. Score**	**IT- South Platte Avg. Score**	**Total Avg. Score**
Content Knowledge	Con	1.07	1.29	1.27	1.20	**1.21**
Critical Thinking Skills	Think	1.64	1.29	1.20	1.20	**1.33**
Scientific Components	Comp	1.93	1.71	0.93	0.87	**1.34**
Data Collection	Data	1.64	2.00	1.40	1.07	**1.52**
Hypothesis	Hypo	1.36	1.20	0.33	0.53	**0.86**
References	Refs	0.29	0.00	0.27	0.13	**0.17**
Standards	Stds	0.00	0.00	0.27	0.40	**0.17**
Experimental Design	Design	1.71	1.57	0.93	1.07	**1.31**
Creativity	Create	2.00	2.00	1.20	1.60	**1.69**
Organization/ Coherence	Org	1.86	2.00	1.53	1.47	**1.71**
Class Avg. Score on Modules (%)	ITSP, ITC, Physical, Anim	76.4	72.8	57.6	61.4	**67.1**
Mid-term Score (%)	Midterm	N/A				**65.0**
Final Score (%)	Final	N/A				**61.5**
Course Final Grade (%)	Grade	N/A				**71.3**
GPR (4-point scale)	GPR	N/A				**2.74**

Table 8

Examples of student imperfect conceptions revealed during mental model development

Student	Response	Area of limitation
A	"The reason bacteria degrade the molasses faster than the oil is because the oil **molecule** is bigger than the bacteria **cell**".	Linking of scales
B	"A **reduced** environment has **aerobic** processes".	Content knowledge
C	"**Pyrite** exists where **oxygen** is readily available".	Content knowledge
D	"The **black** material produced in the sediment is **bacteria**".	System understanding

Figure 1. Relative importance of principal components

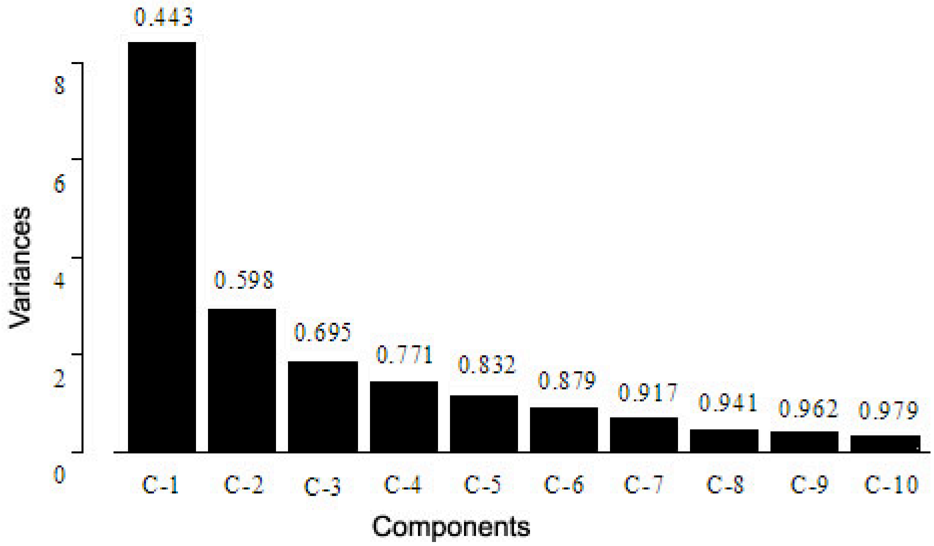
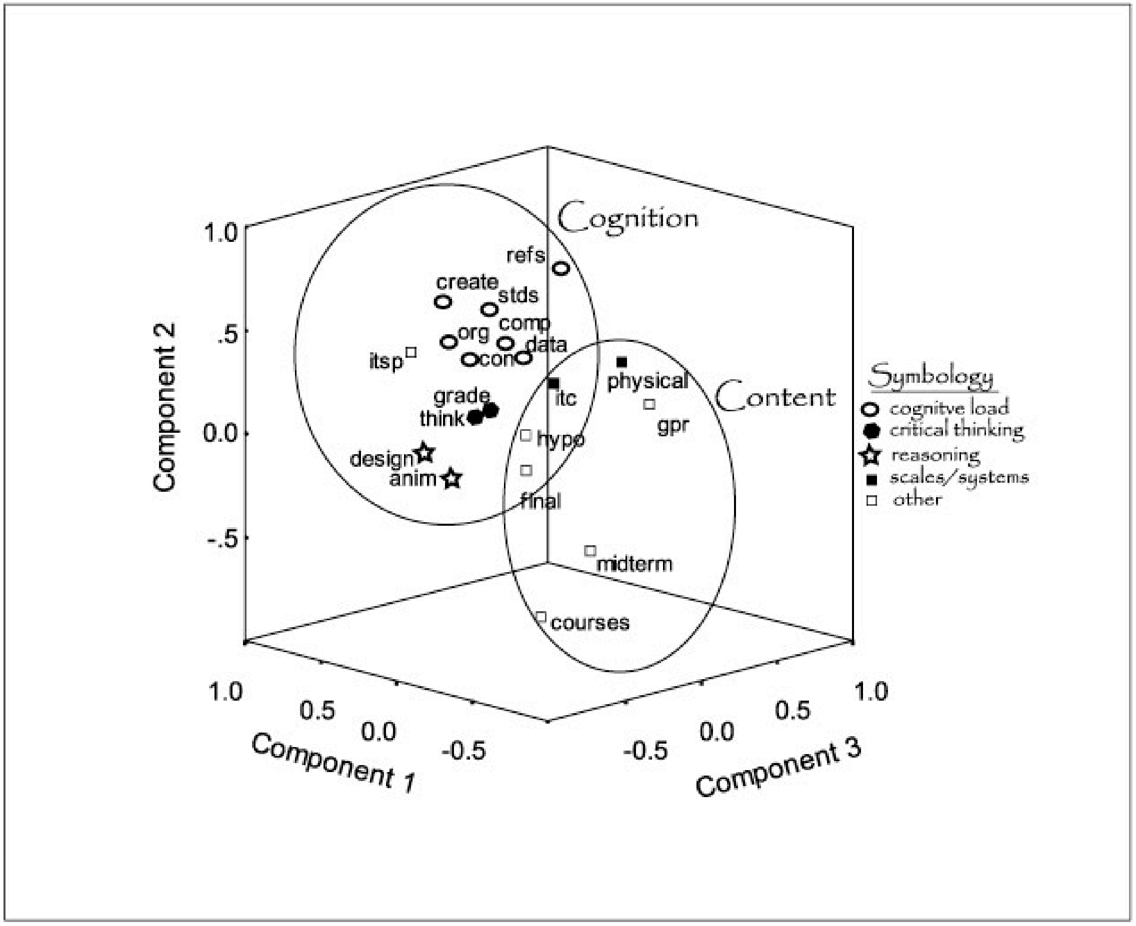


Figure 2. Factor loadings for components 1,2, & 3.



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