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Introduction to the Issue

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For this special issue of *JSET*, we have assembled five important papers based on research at the Concord Consortium. These papers report new developments in strands of ongoing research and development that are among the most promising ways to realize the educational potential of information and communication technologies (ICT). The goal of this Introduction is to place these papers in their larger context and to indicate some of our expectations for future developments in these areas.

COMPUTER AND MENTAL MODELS

One of the most exciting roles for computers in science education involves incorporating computer models of scientific phenomena into well-designed science learning activities with the goal of generating and refining the mental models that learners construct and use to understand their world. Three of the papers in this issue address aspects of this topic. The paper by Buckley, Gobert, and Kindfield reports learning using a computer model of classical Mendelian genetics; the Gobert and Pallant paper uses a model of plate tectonics; and the Pallant and Tinker paper is based on a sophisticated molecular dynamics computational model. While these three models differ considerably in content, computational complexity, and technology, they all are designed to support student exploration on the basis of manipulating computer models.

Computer models are important tools for learning since they can and represent spatial information that is difficult to represent in textual form. The technology makes it possible to simulate the causal and dynamic aspects of complex phenomena in ways that can foster deep science learning. By providing software controls, students can make manipulations and observe the different outcomes on the basis of these manipulations, thereby, engaging in deep authentic inquiry with models.

Underlying our approach is a theory of model-based learning and teaching which guides both our model development, curricular materials, and tasks. Briefly, we define model-based learning as a dynamic, recursive process by which learners construct mental models of scientific phenomenon. Reflective interactions with computer models are helpful in constructing, revising, and elaborating mental models. Scientific concepts are challenging because they often involve causal reasoning, and scales of time and space that are unfamiliar. Models that allow students to manipulate the relevant variables and simulate their behavior are an excellent way to promote deep understanding of these difficult-to-understand and invisible causal processes. Learners need guidance or scaffolding when learning from models to guide their attention to the important information in models. Scaffolding also provides suggestions, challenges, opportunities for reflection, and feedback as they explore computer models. To provide this structure, The Concord Consortium has developed a model control environment called *Pedagogica* (Horwitz and Christie, 1999). *Pedagogica* can take control of a model, reduce the options available in a particular context, provide context-sensitive help, questions, or encouragement, and link to other *Pedagogica* pages to create a branching activity. *Pedagogica* can also react to student choices and forward information about these choices to remote researchers. Because of this data-collecting capacity, *Pedagogica* is an important tool for research, first used this way in the research reported by Buckley, Gobert, and Kindfield.

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Because it is general, *Pedagogica* can be linked to any software model or tool to create scaffolded model exploration activities and embedded assessment. Various projects at The Concord Consortium have combined *Pedagogica* with models for genetics, mechanics, molecular dynamics, system dynamics, and chemistry. This flexibility allows us to produce consistent model-based learning activities for high school biology, chemistry, and physics, and to study in detail the long-term impact of student exposure to these models over several years as part of the Modeling Across the Curriculum (MAC) project.[3] Because the model-based materials can be delivered online, we are able to study this approach in several schools scattered throughout the country.

The molecular dynamics models running under *Pedagogica* that are reported by Pallant and Tinker provide the basis for innovative improvements in teaching in all the sciences. In these models, many of the physical and thermodynamics properties of materials emerge from the fundamental forces between atoms and molecules. This suggests that sufficient engagement with these models will foster the development of mental models of atomic and molecular systems; these mental models have generative power such that they can support students' reasoning. The initial evidence reported indicates that student learning of the states of matter can be earlier than expected and transferred to new contexts. If these results can be extended to other content areas, molecular dynamics models may make an important contribution to science learning.

PROBEWARE HANDHELDS

Jack Wilson, president of the University of Massachusetts, once remarked that probeware was the single most important educational innovation enabled by microcomputers. Probeware—sensors, interface electronics, and software to collect, display, and analyze real-time data—create extensive new opportunities for students to learn about the natural world through experimentation. The real-world nature of probeware is a useful counterbalance to the simulated world of computational models.

The core probeware team at The Concord Consortium started its work in 1978 at TERC. That led to research in the mid-1985 that demonstrated the value of probeware to learning some important and difficult physics concepts. Ron Thornton showed that neither lectures, problem sets, nor conventional labs, singly or in combination are able to convey crucial mechanics ideas the way a set of well-constructed probeware-based activities can (Thornton, 1997).

In spite of this long history and the presence of many fine products on the market,[4] probeware use is marginal, particularly in elementary grades. This is, in part, because it has not been incorporated into science curricula. Of the 22 NSF-funded science curricula for grades 3–8 featured the EDC Dissemination Center,[5] not one exploits probes or any other current technologies. Commercial texts and basal series also avoid probeware. Explanations for this avoidance of proven, commercially available probeware can be traced to the costs of implementation, the expense of TPD, the lack of good curriculum materials, and the relative paucity of research results. We are particularly alarmed by the inequity of access to probeware because there are indicators that school wealth is associated with probeware use and this is associated with higher performance on the NAEP science tests.[6] To address these problems, we have been experimenting with reducing implementation expenses by shifting to handheld computers, developing low-cost hardware, and experimenting with less-expensive online teacher professional development.

The paper by Metcalf and Tinker describes some initial results with this new approach. It reports on student learning with handhelds and low-cost probeware that were created for this study. We developed units that addressed common middle-school science education standards for energy conversion and mechanics. As hypothesized, middle-school teachers were able to implement curriculum units with probeware and handholds as judged by student gains, even teachers who had no face-to-face contact with the project staff.

This research should prepare the way to more extensive and rigorous studies of inexpensive probeware for young learners. The next step is to test learning materials that cover more of the science curriculum, expand the studies across grades 3–8, and to include effective controls. Our goal is to provide inexpensive probeware alternatives for the entire upper-elementary and middle-school science curriculum that will be easily integrated with texts and NSF curricula. To encourage schools to adopt these

[3] See http://mac.concord.org/

[4] See http://probesight.concord.org/

[5] See http://www2.edc.org/cse/work/k12dissem/materials.asp

[6] See http://nces.ed.gov/nationsreportcard/pubs/main2000/2002452.asp

materials, we plan research that compares student learning in classes over 2 years, with probeware used only during the 2nd year.

ICT ENABLED COLLABORATION

Communications technologies that support learning through collaboration between learners has by now a significant history. Some of the earliest work began with the Kids Network (Tinker and Papert, 1989), Computer-Supported Intentional Learning Environments (CSILE) (Scardamalia *et al.*, 1989), the Kids as Global Scientists project (Songer, 1996), and the Global Lab at TERC, and The Concord Consortium (Berenfeld, 1994). Student–student collaboration is central to the best online courses based on a scheduled, asynchronous model (Tinker, 2001) as implemented in the Virtual High School and related online professional development (see next section).

These and other projects demonstrate that well-structured, facilitated peer collaboration has many advantages. One important aspect of collaborative tools is that they allow for learners to collaborate while removing the biases that are present in the regular classroom, that might be based on socioeconomic factors, ethnicity, perceived "rank" in science, or disabilities. Participation in well-facilitated online collaborations can be more equitable and foster the fuller engagement of less verbal or more retiring students. Online writing is often more thoughtful than corresponding class conversations. Online collaboration leaves a written record that can be used to help students reflect and assimilate other views.

Web-based learning activities tend to avoid peer collaboration because the technology is oriented toward server–client rather than client–client communication. Supporting learner collaboration is not impossible in Web-based applications, but it does require an additional level of technology to support messaging, student registration, and security. As a consequence, there has been a tendency to omit peer collaboration in Web-based curricula. The various hypermodels built from *Pedagogica* do not support such collaboration, nor did the original version of the Web-based Inquiry Science Environment (WISE), a powerful Web-based curriculum development and delivery system (Linn and Hsi, 2000).

The paper by Gobert and Pallant in this volume illustrates a WISE project which leverages from the WISE technology and design principles of the UC-Berkeley team and combines this with well-scaffolded model-based activities which are designed to promote both students' content knowledge of the domain as well as students' understanding of the nature of models. What is atypical of this project is the way in which the driving question "Why are the plate tectonics on the West and East coasts so different?" is used to engage students in a cross-continent virtual collaboration. The data from this project demonstrate large learning gains in content as well as epistemological thinking.

WISE needed to be enhanced to support the East–West collaboration built into the instructional materials. It is a tribute to the WISE software design that the required enhancements were relatively easy to add to the existing WISE infrastructure. This project serves to remind us all of the importance of including peer collaboration in all ICT platforms by demonstrating how learners can build their knowledge together to create communities of learners. This is an important part of maintaining and evolving scientific practice and lifelong learning.

ONLINE TEACHER PROFESSIONAL DEVELOPMENT

Online teacher professional development has proven to be an important and, if properly designed, effective way of supporting teacher growth. We started experimenting with this at the time The Concord Consortium was launched. This early experience gave us the confidence to launch the Virtual High School,[7] which depends on entirely online courses to train teachers to develop and offer VHS courses (Zucker *et al.*, 2002). This experience has led us to rely on a facilitated, asynchronous design that is reliable, economical, and effective (Collison *et al.*, 2000; Tinker, 2001).

This design was critical to the research reported by Metcalf and Tinker, because part of their effort to demonstrate inexpensive probeware implementation required showing that typical teachers could implement probeware at the middle-school level without expensive face-to-face workshops. Online TPD is also an important tool in the MAC project reported in Buckley, Gobert, and Kindfield.

Over the last 5 years, we have been experimenting with improving online TPD with the use of video case studies. Nemirovsky and Galvis report on some

[7] See http://govhs.org

of this work, using video cases of elementary mathematics classes as a focus for online discussions about content and pedagogy. They focus on teacher responses that are grounded in the case studies or their own teaching and suggest ways of eliciting such responses. Their study indicates that grounded discussions, when facilitated expertly, can result in thoughtful reflection about teaching and learning.

Nemirovsky and Galvis are now exploring the value of teacher-generated video case studies that can be shared online with peers and annotated by them. We imagine that a video case might become an object that a team of teachers can analyze together, sharing observations, insights, and suggestions. In collaboration with TERC, we are currently developing open source technology that facilitates this[8] and are studying the value of using such technology with teachers. If teachers can manage the technical aspects of producing and editing a video of their teaching and they have sufficient self-confidence and sense of safety to share it with their peers, this should be more meaningful and effective than "canned" videos.

RESEARCH METHODOLOGY

The paper by Buckley, Gobert, and Kindfield demonstrates our first use of online embedded assessment with model-based learning activities. This approach, developed in the MAC project, supports remote data collection from large numbers of students that is very fine-grained at the individual student level. The project involves a cohort of approximately 19,000 students who are being followed for 3 years across their biology, physics, and chemistry classes. The embedded assessment tools address important issues about HOW students are using our models to learn with. For example, we can study the exact length of time a student took on each screen, the types of manipulations made to the model, the responses and explanations generated by the student, and the help requested. From these data, we expect to be able to develop canonical models of what skilled versus unskilled students do in learning with interactive models which, in turn, can be used to develop pedagogical supports. The logging feature of *Pedagogica* that is used by researchers for data and by teachers for formative and summative assessment is one of the cornerstones of the MAC project.

The embedded assessments are given at pivotal points in the MAC hypermodel activities and designed to both keep the student engaged and provide formative assessment for the teacher. When the teacher views a teacher report generated by *Pedagogica* after a pivotal point in the activity, s/he can see, for example, how many students answered each item correctly or incorrectly. S/he could then look at the individual log files (saved as a special form of teacher report) of the students who got these items incorrect and ascertain whether the students were unmotivated (i.e., marked by very short reading times) or whether the student had difficulty understanding the concepts in the activity. This provides teacher a data-driven method of assessing students during the unit as opposed to waiting until the unit is complete when there is little or no time to review the material. Furthermore since the teacher has a "bird's eye view" into what the student did online, s/he can provide much more individuated feedback to the students.

While this kind of detailed student assessment has always been a feature of computer-assisted instruction (CAI), our approach is based on a more powerful instructional strategy than most CAI, namely model-based activities. Furthermore, we can collect data about the student use of models that will provide more subtle insights into student thinking than the multiple-choice items usually used in CAI.

This capacity for detailed large-scale studies of student learning represents a new methodology for educational research. One of our goals is to make this technology available to other researchers much the way technologies such as particle accelerators and large magnets are made widely available to science researchers. To draw attention to this parallel, we have named this collection of technologies, experts, and materials, the Education Accelerator, and are making it available to the research community through the Technology Enhanced Learning of Science (TELS) Center. TELS features a collaboration with the WISE group at UC-Berkeley which also has technology that is used in large-scale studies with embedded assessment. TELS is a 5-year NSF-funded Center for Learning and Teaching that will enable us to combine and improve *Pedagogica* and WISE capacities and use the resulting capacity for collaborative research.

To foster increased use of this exciting new research methodology, we are making *Pedagogica,* all the computer model engines, and the resulting hypermodels available free from our website to any user or institution. We will also provide the source code

[8] See http://vpb.concord.org/

for *Pedagogica* and the models under an open source license that permits anyone to modify and improve the software, providing that the modified versions are also made available on the same basis. Our hope is that educators and researchers worldwide will take advantage of these innovative resources for education and research.

ACKNOWLEDGMENTS

The five papers in this special collection draw from important strands of research and development that are addressing some of the most promising educational applications of ICT: modeling, probeware, online collaboration, online courses, and large-scale research. That a small organization like The Concord Consortium is able to contribute to advances in all these areas is a tribute to the 50 dedicated staff at The Concord Consortium and their ability to collaborate on large projects. Each of the projects contributing to these reports is a joint effort of outstanding researchers, teachers, programmers, curriculum developers, staff trainers, video producers, and support staff at The Concord Consortium and at our many collaboration institutions, particularly TERC, the University of California, Berkeley, Northwestern University, Harvard University, SRI, and participating schools.

Downplayed in the research papers is the huge technical development effort required. The many computer models, the *Pedagogica* platform, the portal that supports student and teacher registration and data capture, and the probeware, all require sophisticated software that must be robust, dual-platform, and able to run in typical school. This effort is coordinated by Paul Horwitz and implemented by a talented team of programmers to whom we are indebted.

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