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Next-Generation Educational Software: Why We Need It and a Research Agenda to Get It



THE DREAM OF UNIVERSAL ACCESS to high-quality, personalized educational content that is available both synchronously and asynchronously remains unrealized. For more than four decades, it has been said that information technology (IT) would be a key enabling technology that would make this dream a reality by providing the ability to produce compelling and individualized content, the means for delivering it, and effective feedback and assessment mechanisms. Andries van Dam, professor of computer science and vice president for research at Brown University, notes that although IT has certainly had some impact, it has become a cliché to say that education is the last field to take systematic advantage of IT. Van Dam acknowledges the immense challenge of creating next-generation educational software but emphasizes the imperative to lay out a research agenda, or roadmap, and begin the hard work of fulfilling IT's promise for education.

IT's Role in Education

Generally, IT's role in education is to augment, not replace, the teacher; to provide human-centered tools that encourage and support adaptability and flexibility; and to enable a variety of learning modes such as remote and colocated small team interaction and individual task performance. Current technologies can readily support interactive involvement of the learner with educational materials and situated active learning by doing (as opposed to just by listening).

However, one size does *not* fit all in educational software. Unless new tools allow exploration at multiple levels of detail and accommodate diverse learning styles, they will be just as limited as ordinary textbooks. But this is easier to say than to do: There is no collective experience in authoring at multiple levels of detail and multiple points of view. Such authoring requires the development of skills and tools of far

greater power than we have experience with to date; the Learning Federation and “clip model” discussion below addresses some of the research issues involved.

In addition, we must also train educators to take advantage of these new capabilities—a task that will require massive investment on a scale we have not encountered heretofore. New content creation, curricula adaptation, and educator training will also require a long period of experimentation and tolerance for the false starts that are an

inevitable part of all innovation processes.

Learning Federation Research Roadmaps

The Learning Federation (<http://www.thelearningfederation.org/>) was created to better understand the issues involved in IT-enhanced education and to direct a focused research investment effort. It is a partnership joining companies, colleges and universities, government agencies, and private foundations whose purpose is to provide a critical mass of funding for long-term basic and applied precompetitive research in learning science and technology. This research, to be conducted by interdisciplinary teams, is meant to lead to the development not only of next-generation authoring tools but also of exemplary curricula for both synchronous and asynchronous learning.

The Federation’s first task was to produce a Learning Science and Technology R&D Roadmap. This roadmap describes a platform-neutral research plan to stimulate the development and dissemination of next-generation learning tools, with an initial focus on postsecondary science, technology, engineering, and mathematics. The component roadmaps address five critical focus areas for learning science and technology R&D:

- **Instructional design: using games and simulations in learning.** Learning environments that provide opportunities

to apply knowledge to solve practical problems and invite exploration have been shown to lead to faster learning, greater retention, and higher levels of motivation and interest.

- **Intelligent question generation and answering systems.** Question generation is understood to play a central role in learning, because it both reflects and promotes active learning and construction of knowledge.

- **Learner modeling and assessment.** Assessment generates data for decisions such as which learning resources to provide individual learners. These decisions are only as valid as the data and interpretations that are available.

- **Building simulations and exploration environments.** Simulations used in academic settings can enhance lectures, supplement labs, and engage students. The goal is to make simulations and synthetic environments easier to build and incorporate into learning environments.

- **Integration tools for building and maintaining advanced learning systems.** A variety of authoring and integration tools are needed to make it easier to identify and use software resources. Designers should be able to focus entirely on content and the needs of students, and not on the mechanics of the software.

Beginnings at Brown University

The Brown computer graphics group has long been particularly interested in building simulation and exploration environments—often referred to as “microworlds”—partially inspired by Alan Kay’s powerful Dynabook¹ vision along similar lines. As our next phase of microworld development research, we are working on pen-based gestural interfaces for tablet PCs. Two applications using such interfaces are MathPad² and ChemPad.

MathPad²

Mathematical sketching is a pen-based, modeless gestural interaction paradigm for mathematics problem solving. Although it derives from the familiar pencil-and-paper process of drawing supporting diagrams to facilitate the formulation of mathematical expressions, users can also leverage their physical intuition by watching their hand-drawn diagrams automatically animate in response to continuous or discrete parameter changes in their written formulas. Implicit associations that are inferred, either automatically or with gestural guidance, from mathematical expressions, diagram labels, and drawing elements drive the diagram animation. Users can switch freely between modifying diagrams or expressions and viewing animations. Mathematical

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sketching can also support computational tools for graphing, manipulating, and solving equations. (See Figure 1.)

ChemPad

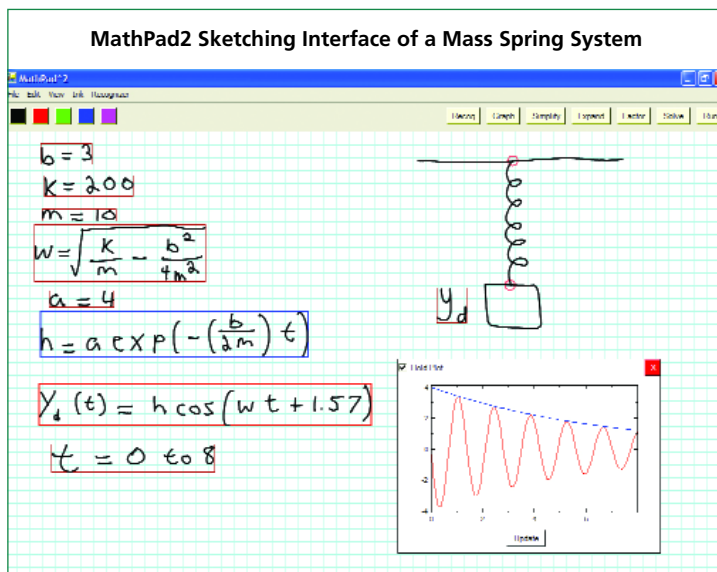
Teachers of organic chemistry identify spatial understanding of the complex three-dimensional structures of molecules as a key determinant of whether students will succeed in organic chemistry. We have been designing and developing a software project, ChemPad, whose purpose is to help organic chemistry students develop an understanding of the 3-D structure of molecules and the skills to construct a 3-D mental model of a molecule that matches a 2-D diagram. ChemPad fosters this understanding by allowing the student to sketch a 2-D diagram and then to see and manipulate the 3-D model described by the diagram.

A pen-based interface is particularly appropriate for drawing organic chemistry molecules because the existing software tools in this area are difficult to learn and use, which places them out of the reach of most students. Drawing with pen and paper, though, is not entirely satisfactory; it is difficult to produce clear drawings, and it is difficult to erase and correct errors neatly. ChemPad addresses both these issues with a simple interface that mimics drawing on paper, and a “beautify” function that tidies up a student’s drawing. ChemPad also provides validity checking; many of the structures that beginning students draw do not describe physically possible molecules. Unlike paper and pencil, ChemPad can detect and indicate certain kinds of errors.

Clip Models: Next-Generation Educational and Research Software

Although the microworld projects developed so far have been useful adjuncts to undergraduate courses, they fall short of the goals of a far more ambitious vision since they are restricted to single concepts with a small set of parameters. However, because they are component- and parameter-based, they illustrate some of the fundamental principles that will be essential in the fully functioning clip-model environments described below, and they open possibilities for evolving even more flexible structures.

Figure 1.



The “spiral approach to learning” common to formal education—in which a learner encounters a topic multiple times throughout his or her education, each time at an increasing level of sophistication—provides a model for next-generation educational software. At any stage, the learner should be able to mix and match educational modules at different levels of sophistication within the same general topic area. Simpler modules can offer overviews of a subject for review or provide context when the intent is to go more deeply into related topics.

The kinds of modules we are most interested in here are simulation- or rule-based modules that help create explorable models of subsystems, which can be linked into increasingly higher-level subsystems. Such modules can help simulate most aspects and components of the natural and man-made worlds.

For example, as shown in Figure 2, to simulate the human body we must simulate the subsystems at all levels, from the molecular to the cellular to the gross anatomical. Each subsystem of the human body must then be simulated at a level appropriate to the educational purpose. There is not just a single model/simulation for each component of the system (e.g., the heart or lungs) but a family of models/simulations varying in explanatory power and simulation fidelity—not to mention, ideally, in the learning style it is to match. Furthermore, since subsystems interact with each other, the models and their underlying simulations must be able to interoperate.

We summarize the properties of these types of models

with the term “clip models”: simulation-based families of components that represent multiple levels of explanatory power and simulation fidelity designed to interoperate and to be assembled into systems. In particular—unlike clip art, which represents only images—clip models emphasize behavior, interaction/exploration, and interoperability.

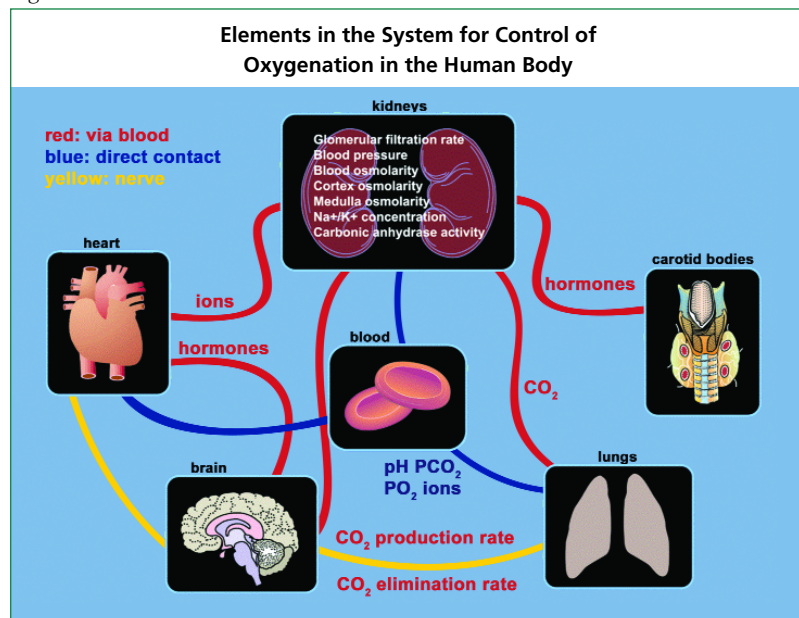
This concept of mix-and-match, multi-LOD (level of detail) models poses huge challenges to would-be implementers. The inherent challenges of building multiresolution, multiview, multicomplexity interoperating simulations have not yet been confronted because most simulation efforts have been standalone projects. In the same way, repositories of learning objects have stored objects at just a single level of explanatory power, and component frameworks in use by software developers have not been designed with the complexity of interoperation between components at different levels of detail in mind.

Conclusion

Creating high-quality next-generation educational content across all disciplines and at all levels will require a grand challenge effort on the scale of the Manhattan Project, the Apollo Moon Project, and the Human Genome Project. The United States, European, and several Asian economies have both the ability and the need to cultivate the will to invest the same amount in creating exemplary interactive courses as they do in videogames and special-effects movies. The payoff from the massive investment of time, energy, and money cannot be overstated.

Beyond education, clip-model architecture will help advance science itself. The architecture will enable the

Figure 2.



development aspect of R&D to rapidly integrate advances in basic research. We cannot predict the insights that will be revealed by happy accident when unrelated strands of knowledge are unified in an integrated model, but we can eagerly anticipate the leverage and new knowledge that will be gained from the synergy.

1. For his current work, see <http://www.SqueakLand.org>.

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