Reflections on Next-Generation Educational Software

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Prologue

I am honored to be able to contribute to Bernard Levrat's FestSchrift. I had the pleasure of working with him at the University of Geneva during my sabbatical in the late 1970s and treasure the memories of our wonderful times together in the great outdoors, both in Switzerland and in California. During those hiking and cross-country skiing trips and many enjoyable gourmet adventures, the discussion often turned to our career-long shared interest in the appropriate use of computer technology in all aspects of education. Although Bernard is retiring from the University of Geneva, he is obviously having great impact on the use of information technology for new forms of education through his leadership of the Swiss Virtual Campus Project [SVCP 2001]. This trend-setting effort, along with other efforts around the globe [EFODL 2001, OU-UK 2001, Universitas 2001], will transform our current notions of conventional, synchronous, campus-based university education that are still founded largely on the German university model of the nineteenth century. While I cannot foresee all the long-term implications of changes in educational authoring and delivery mechanisms, let alone educational institutions, I do want to speculate here a bit on trends and to advocate a particular vision of what I hope will come to pass in the relatively near future.

"For the times they are a'changin'" – Bob Dylan, 1964

It is clear that this is a time of evolutionary, and soon, revolutionary change in our society. As lifelong employment in "one's chosen profession" disappears and professions continuously transform themselves, there is an increasing need for workers to be able to adapt to rapid changes, learning new skills and entirely new fields throughout their working life. Learning to learn is already becoming the most important skill, along with the focus on critical thinking, problem solving, and innovative discovery. Aiding this shift towards an adaptive, dynamic lifetime career focus are continuous technology improvements that make new approaches both available and affordable. Below I summarize some of these trends and their implications for education.

Needs

- We need mechanisms, infrastructure, and organizations that enable lifelong learning based on just-in-time, on-demand, and asynchronous as well as synchronous learning. The bottom line is that education needs to be available to everyone, whenever and however they need it. Instructional materials for this mode of learning won't necessarily fit the mold of traditional courses, let alone standard course sequences or indeed curricula. For example, instructional modules may involve only prerequisite chains for any given topic and be arbitrarily interlinked with related modules.

- Current educational practices, particularly in the sciences, mathematics, and engineering, produce far too many graduates who can solve standard academic problems but can't solve real problems, much less problems whose nature and solution spaces change as one attempts to solve them. Moreover, many of these students are inexperienced in qualitative reasoning, a fact that has led to the qualitative physics movement, pioneered by Ibrahim Abou Halloun and David Hestenes at Arizona State University [Halloun & Hestenes 1985a, Halloun & Hestenes 1985a] and Ruth Chabay and Bruce Sherwood at CMU [Chabay & Sherwood 2001], and a new form of teaching called Peer Instruction developed by Eric Mazur at Harvard University [Mazur 1997].

- Education needs to be much more constructivist, "learning by doing" using real problems that are appropriately scaled down, in as real an environment as can be conceived. This process often involves multidisciplinary approaches. For example, solving a simple problem dealing with the environment may involve chemistry, biology, climate, population dynamics, etc. Thus we see case-based and problem-based approaches, typically demanding team efforts, and studio courses either enhancing or replacing traditional lectures and standardized testing [Lister 1998].

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Enabling Technologies

- Moore's Law and clever device engineering show no signs of slowing down.
- Networking is becoming more ubiquitous, faster, and cheaper, making the Web a powerful distribution mechanism.
- Form-factor explosion allows pervasive computing because interconnected computers can exist not only on the desktop but also in our buildings, and even in our furniture, clothing, and bodies. Thus we are moving closer to the dream of a continuous computing environment that seamlessly follows us wherever we are.
- 3D graphics chips and cards create revolutionary improvements in the real-time display of dynamic, interactive graphics, allowing for the manipulation of objects that enables virtual construction to reinforce principles of design and content.
- Real-time streaming video and audio can now be handled through proper compression, even on commodity machines and low-bandwidth connections, and thus are no longer confined to higher-end machines.
- Thus, we can contemplate running sophisticated simulations in real-time on commodity desktop and laptop computers, showing rich sensory information – graphics and audio in particular – that was not possible even five years ago.[1]

Institutional Impact

- Traditional universities, consortia of universities, and companies (often partnered with universities) are all getting into the Web-based distance-learning act. In the U.S., for example, UNext, University of Phoenix Online, Blackboard, and GEN are well-funded and trying to develop partnerships, courses, and a clientele. Institutional distance education, which just a short time ago was viewed by the educational establishment as of marginal interest, is now becoming a mainstream activity. For example, the ambitious EU European Commission's "eLearning Action Plan" reflects the strong European experience and interest in open and distance learning that can be seen in such institutions as the 40-year-old Open University of the UK [OU-UK 2001]. Additional consortia include European Federation for Open and Distance Learning [EFODL 2001], Universitas 21 [Universitas 2001], and the Swiss Virtual Campus project [SVCP 2001]. This interest is also reflected in pioneering educational infrastructure projects such as Fraunhofer IGD's Modular Training System (MTS) project [MTS 2001].
- With the advent of the Web, it has become popular for professors to put their instructional materials online, up to and including syllabi, course notes, and even textbooks, as well as to offer streaming video of lectures with correlated lecture slides. For example, in my introductory Java course at Brown my lectures are available via Classroom 2000 [Classroom 2000] indexed to my lecture slides, as well as are my course notes (Bernard has used my lecture slides in his own course).
- In developing countries as well as developed countries there is an increasing drive to provide quality education for all, not just a privileged elite. This drive comes about in part because technological changes, such as the Web, make new approaches both more thinkable and more feasible. Perhaps more pertinent, however, is the growing perception by top universities that to survive they must address the competition presented by for-profit companies that are attracting high-quality talent – their own professors. For example, we are seeing a major change in mindset

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[1]Of course, that one can get a well-loaded PC in the US for under $1000 doesn't alter the fact that developing countries are still a long way from an affordable solution on their economic terms. However, in the same way that TV has penetrated even remote disadvantaged regions, so too will PCs and the Internet when they become sufficiently commoditized and compelling.

by schools such as MIT, which is making all its course materials available for free on the Web in a new initiative called MIT OpenCourseWare (MITOCW) [MIT 2001], in effect protecting its 'brand' by demonstrating its quality in the widest possible way.

- Although companies have been engaged in online training efforts for some time, the involvement of entire universities and consortia of universities in online learning marks a shift in focus caused by a growing awareness that education in the future may look quite different from now. As more traditional types of university courses emerge online for lifelong learning audiences, the distinction between training and learning is becoming less meaningful. Companies and institutions have begun to exploit this fact, offering products that provide the complex infrastructure necessary for such efforts.

- As education access becomes less synchronous and time-of-life-oriented and more asynchronous, just-in-time, and on-demand-based, we will see a new framework of educational service levels, analogous to the different levels of service seen in software service contracts:

  1. Free – available on the Web, e.g., MIT OpenCourseWare, with no support

  2. Subscription service on a per-unit or yearly basis, as is done in digital libraries – in the ACM digital library you can pay by the year or by the paper

  3. For-credit individual distance courses – extension of the Open University idea, with online tutors/mentors (this is widely available already, especially in such high-demand fields as business)

  4. Full accredited degrees from top schools, but through distance-learning methods

  5. Full on-campus, in-residence degrees, perhaps via satellite sites limited to the main campus

  6. Full industry certification from companies like Microsoft, IBM, Cisco, and Novell, as valuable as degrees in the eyes of many employers

  At all levels, issues of access to scarce resources, e.g., master teachers, tutors/mentors, and laboratories, must be addressed.

Educational Design, Structure, and Delivery

Despite some success stories, I believe that education is, unfortunately, an application area that lags virtually all others in its effective use of computer technology. K-12 schools and universities teach much as they have in the past hundred years, largely unaffected by IT (although at most universities at least word processing is finally ubiquitous). The notable successes, however, include classical CAI for fact and skill acquisition, reading tutors, cognitive tutors/instructional tutoring systems for high-school algebra and geometry, SimCity and its relatives, and the graphing calculator. Certainly future instructional materials will continue making use of CAI, instructional tutoring systems, and streamed lectures embedded in hypermedia e-books.

I advocate a concerted effort to start building next-generation materials, designed for next-generation computing environments that have an order of magnitude higher level of computing and graphics power to facilitate improved communications, improved visualization and simulation, and improved interactive feedback systems for accelerated learning. My focus is on an extension of today's virtual laboratories, i.e., fully interactive experiences based on underlying parameterized behavioral simulation models. The idea is to have each concept in a field illustrated not by a static picture or a simple canned animation but by a fully explorable microworld embedded in a hypermedia environment. We call such interactive illustrations "exploratories" to suggest a combination of a science museum exploratorium and a more guided, problem-solving laboratory. This idea is based on constructivist learning theories as advocated by such educational software pioneers as Alan Kay and Seymour Papert [Kay 1993, Papert 1993] **.**

Interoperable Families of Clip Models

Forty years ago Jerome Bruner in the **Process of Education** [Bruner 1963] proposed that any subject could be taught with integrity to anyone at any level. While many have disputed the more extreme claims attaching to that hypothesis, it is a valuable though difficult goal. Not only will this mean that a spiral approach to component-based learning becomes possible, it also means that the same person can mix and match modules at different levels within the same general area. Simpler modules can serve as overviews to a subject for review or to provide context when the intent is to go more deeply into related but different areas.

In the Exploratories project at Brown University, we create this type of content [Exploratories 2001] and work on defining strategies for this approach to educational software. For the last four years we have been developing a collection of interactive models that provide point support for different conceptual levels in my introductory computer graphics course. Many of the strategies we have been investigating, from use of hypertext design patterns to level of granularity of learning objects, are discussed in the project's published papers [Beall et al. 1996, Gould et al. 1999, Laleuf & Spalter 2001, Simpson et al. 1999, Spalter et al. 2000a, Spalter et al. 2000b, Spalter & Simpson 2000a, Spalter & Simpson 2000b].

Following Bruner's hypothesis, we have been studying a new design guideline in which multiple levels of abstraction or sophistication of models are used to explain a concept. A single exploratory can only represent a single level of model sophistication but, for any given concept, different levels of model sophistication are necessary to educate students.

For example, a high-school student is often introduced to concepts in cell biology with a simplistic mechanical-looking model of a generic cell. As a student progresses in biology, however, the model used must progress as well to better represent organic complexities and remove oversimplification. The same is true in atomic physics: the Bohr model is still used to introduce the concept of the atom, but higher-level students learn a much different model, one that is less easily visualized but takes into account quantum-mechanical effects.

Thus designers must think not in terms of a single "clip model" that they can embed in their own explanation, but of a interrelated family of clip models or simulations that cover a broad range of the representations used in a field. The types of interaction one designs depend directly on the nature of the model and thus assume different levels of previous knowledge. Locating an electron in the Bohr model, for instance, is a different task from "locating" it in a more advanced model. These models, or microworlds, must be interoperable across several dimensions of age, knowledge level, pedagogical goal, and individual capability. This means that we need different levels of detail and different levels of sophistication, smoothly integratable within the same reference frame.

For example:

> A K-12 set of biological microworlds provides a spiraling increase in levels of sophistication and level of detail over the same domain, providing age- and understanding-appropriate modules for heterogeneous classrooms, that may be, but needn't be, online as well as onsite. Thus, an advanced student can have access to challenging material while her age-mate, who is less informed or who has learning disabilities, can obtain the level he needs to attain mastery at his appropriate level and move forward.
>
> A student studying anatomy can see overview microworlds of the heart and lungs but drill down into greater detail about the arterial system, all the while retaining the context of, and access to, the related high-level modules. The sidebar, contributed by Randy Hinrichs and Henry Kelly, illustrates a possible sample engineering assignment using information about the human ear.

These microworlds must correctly reflect the semantics and ontology of the subject matter while providing both unparalleled flexibility and time-and-location independence for the students. The challenges that face implementors of this vision are formidable indeed.

Since all the microworlds must have a foundation of physically-based modeling at the appropriate level in order to accurately represent/simulate the scientific domain they are modeling, the challenges include research-level issues of:

- Pure science
- Domain expertise on both broad and deep levels
- Pedagogy and instructional design
- Information structure engineering
- Software engineering
- Systems and user interface design

Within the research areas listed above researchers must address the following issues:

- How to design to accommodate different levels of user knowledge, age, and experience.
- How to provide interoperability of learning objects at different levels of detail. Note that the interoperability needed involves not only the familiar problems of component-level design, but also much deeper and less understood areas of cognitive, cultural, pedagogical, age, and cross-platform level interoperability.
- Tools and methodologies for creating libraries of clip model families.
- Hypertext infrastructure that facilitates the asynchronous and flexible use of these models.
- Determination of prerequisites and testing modules that can be accessed through the hypertext and Web-based on-demand systems.

Proposal for a Learning Federation

To provide large libraries in all the various disciplines of interoperable clip models embedded in their hypertextual context and integrated with real-time evaluation and assessment is a project of Grand-Challenge scope, involving unprecedented, huge, international commitments of time, personnel, and money. The reasons that it is a Grand Challenge-level project are:

- It is intrinsically open-ended and is likely to grow dramatically as the possibilities become apparent to more and more people.
- Fundamental research is needed, with all that it implies. For example, how do you develop models that can be parameterized and that can have questions asked of them at different levels of knowledge, age, and experience? How do you develop interoperable physically-based models for the heart or for an ecosystem? What parameters should be exposed?
- The infrastructure and user interface design issues have only begun to be addressed.
- The clip models must be designed for the growingly diverse federation of devices that will become the educational vehicles. How is this to be accomplished?
- In short, we must supersede today's repurposed print-based textbooks enhanced with a few additional multimedia bells and whistles. To create next-generation materials centered on interoperable clip models requires a new design discipline for what is essentially a new medium. This design discipline requires collaborative teams of experts from cognitive science, social sciences, the arts and traditional design disciplines, film and other story-telling media, information structure design, and other previously underutilized fields, collaborating with teachers, domain experts, and computer scientists.

To deal with these long-term basic research issues, some colleagues (Henry Kelly, President of the Federation of American Scientists, Randy Hinrichs, Manager of University Research Programs, Microsoft Research, Ed Lazowska, Chairman of the Department of Computer Science at the University of Washington, and Richard Newton, Dean of the College of Engineering, UC Berkeley) and I are proposing the formation of a new organization with a working title of the Learning Federation. The Learning Federation would be a nonprofit, industry-led, industry-governmental foundation to fund research partnerships that focus on closing the education and skills gap through stimulating rapid advances in learning science and technology, as well as the rapid application of these advances. The Learning Federation's initial target will be post-secondary education in science, mathematics, engineering and technology (SMET). The insights gained would clearly be applicable to many other areas and levels of instruction.

The Learning Federation would fund precompetitive basic and applied research, including the development and assessment of prototype next-generation courses and learning environments that would be tested with large numbers of students and teachers. It would fund world-class interdisciplinary teams of sufficient size, longevity, and resources to achieve major advances, and would fund research institutions to identify and test concepts to be moved into practice. It would provide flexible and efficient management designed to identify key research priorities and research providers, manage intellectual property (IP), assess return on investment (ROI), and help disseminate results, and would encourage the formation of new research teams and consortia as appropriate.

Research Strategy

Initially, we propose to pursue seven tightly interwoven research areas:

1. **Learning Science Research**: new approaches to learning and pedagogy, enabled by technology
2. **Content Research and Instructional Design**: build 10-20 revolutionary "exemplar courses" and "exemplar environments" for continuous learning
3. **Evaluation**: judgment about the quality or worth of a student's or a program's performance or progress
4. **Assessment**: observations, measures, and/or tests made to obtain the information needed for evaluation
5. **Learning Tools and Technology R&D**: develop software tools that enable the implementation of learning science concepts in courses and advanced assessment strategies (this is in itself a major research challenge)
6. **Learning Management Systems**: reengineer the business processes of education and develop the appropriate networked learning environments for conducting both the delivery and the business of education
7. **Monitor Innovations in Hardware and Software**: ensure that Learning Foundation work takes full advantage of innovations made in all sectors

The core of Learning Federation activities will be the first four research areas, which form a "virtuous cycle." Instructional concepts developed by the learning science research teams would be immediately put to use by the instructional design teams in a variety of SMET topic areas. The evaluation and assessment teams will develop methods for evaluating individual student progress using innovative, performance-based metrics that measure real gains in understanding (instead of simply measuring skills in passing standardized tests). The learning tools and technology R&D teams will develop key software tools that make the other work possible.

Building real materials, and working with real teachers and learners is essential both to discover problems worthy of further research and to demonstrate the effectiveness of the research results. Donald Stokes [Stokes 1997] points out that researchers like Louis Pasteur working to solve very practical problems achieved some of the most dramatic research discoveries. The close coupling of research teams with people working to develop and test real instructional systems is designed with this strategy in mind.

The research teams will cover the following kinds of problems:

- The ***learning science research*** teams would focus on innovations in learning made practical by emerging technologies. This would include exploring strategies for using learning by discovery and learning by doing, finding how best to use the time and talents of teachers and experts (when to lecture, tutor, coach, counsel, guide, how and when to intervene), learning how to adjust instruction to meet individual student needs, and determining when learning is best achieved in groups.

- The ***content research and instructional design*** teams would support development of collections of interoperable learning objects, as well as complete experimental course units and courses in a variety of different subject areas. They are likely to take dramatically different approaches but will share a number of requirements that will provide challenges to the teams developing learning tools. Developing next generation interactive courses with all their options and possibilities will require many millions of dollars per course, an investment at least as large as that needed to develop today's massive multiplayer simulation-based games. These large costs can be amortized over a large number of learners.

- The ***evaluation and assessment*** teams will provide independent evaluations of innovative courses in experiments involving increasingly large numbers of learners and teachers. All the courses would be designed for continuous improvement and the Learning Federation would facilitate a continuous and expanding cycle of new research, new materials, and new assessments with each cycle of assessment involving an increasing number of students. These teams will also investigate new forms of assessment, including embedded assessment that can track the progress of each student. Embedded assessments can guide the simulated environment to match each individual's level of interest, competence, and learning style and call upon human tutors at appropriate points.

- The ***learning tools and technology R&D*** teams will provide resources for building visually compelling and scientifically accurate simulations, easy-to-use people-to-people tools for connecting groups of students and teachers, and other critical components. The tool designers can also ensure that components can be shared and reused by different groups by basing them on architectures supporting interoperable components. The tools will include authoring systems that make it easy for instructional designers to develop systems based on powerful immersive environments, and that adapt to different learning styles, capabilities, and backgrounds. The tools should be easy to learn and easy to use, letting instructional designers focus on content, instructional design, and teaching.

- The cycle of invention, testing and improvement will be supplemented by work on improving systems for ***learning management*** and a group that will provide continuous intelligence on developments in ***hardware and software*** throughout the economy. The new learning management and administration tools will allow a learner to participate in a wide variety of new learning experiences from many different learning providers. They will also permit uniform tracking of such things as student records, intellectual property, and payments, subject to appropriate privacy protection mechanisms. While a variety of such tools are being developed commercially, enormous opportunities remain untapped. The hardware and software intelligence team will ensure that the Learning Federation teams can take advantage of advances being made outside the field of education.

Conclusion

In this paper I have proposed libraries of clip models, learning objects that are interoperable, that operate at different levels of sophistication, and that may have deep cognitive models of user abilities and level of understanding. While the idea of libraries of learning objects is scarcely new, I know of no successful libraries of interoperable learning objects that address the multiple dimensions I have summarized above. To stress what I said earlier, we need interoperability at different levels of detail that involves not only the familiar problems of component-level design, but also much deeper and less understood areas of semantic, cognitive, cultural, pedagogical, age, and cross-platform level interoperability.

The implementation involves largely unknown, unexplored, and very difficult problems in domain-specific models, in design and assessment, in ontology, epistemology, and pedagogy, and in information structures and associated data structures, in addition to very hard systems engineering and pure science problems. Any hope at all of attaining these goals requires a multinational, multidisciplinary, long-term, Grand-Challenge style commitment. Europe, especially, is providing ambitious initiatives and intellectual leadership that deserve support and close study. Some U.S. colleagues and I are proposing the Learning Federation, a partnership between industries and governments to fund long-term basic research in learning science and technology to be carried out principally at intradisciplinary university research labs. The Learning Federation should collaborate with other such entities around the globe.

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Speculation on a Future Learning Environment

Randy Hinrichs and Henry Kelly

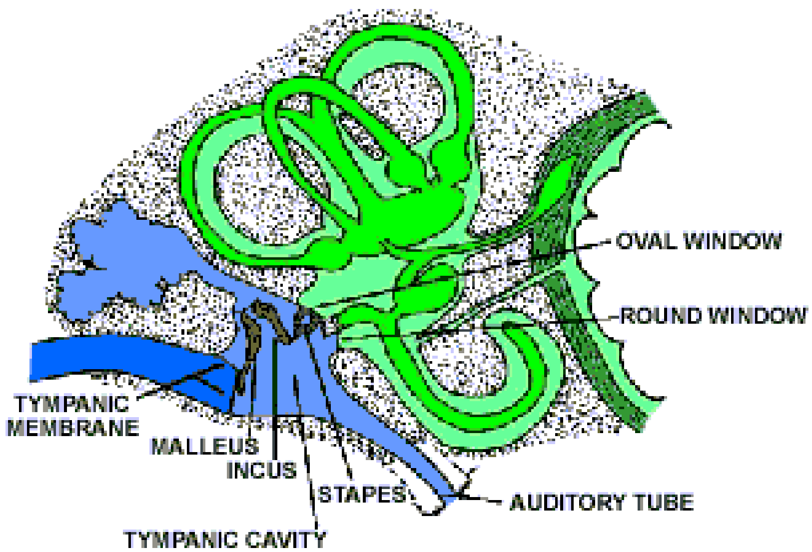
Speculation on a Future Learning Environment

Randy Hinrichs and Henry Kelly

The Assignment

Designers of a course of instruction in Engineering decide that they can develop an interesting assignment by asking a team of students to design a system that can mimic the performance of the human ear.

They discover a complete simulation of the ear is available together with course components developed for use in courses in basic anatomy and histology. The full 3-D renderings in the simulation allows the viewer to see the ear's components in operation from any perspective, at any time scale (e.g. slow motion to follow wave action through the ear), and at any physical scale (gross anatomy to the components in individual cells). The anatomy course offers a series of tutorials illustrating both basic concepts and detailed descriptions of each feature. All are illustrated with the simulation. They typically begin with a "show and tell" by an avatar that walks around the ear's element pointing, and showing the ear's components in action. Experts are available to support the course.



The assignment prepared by the engineering team is to build a functioning ear from a series of components provided (membranes, artificial bones that can be shaped and linked with a variety of pivots and pins (allowing a simulation of wave propagation through the air filled cavities), cavities that can be shaped and filled with a variety of liquids (wave propagation in liquid filled cavities), a variety of vibrating rods and clamps to reproduce the Cochlear hair cells (sensors), and electronic processing components to manage the data from the sensors. The artificial ear will be tested by presenting it with sound at a variety of frequencies and volumes and measuring the signals emerging into auditory nerves. The simulation would also let you hear the input sound and the "output" that would be heard by the person using the ear using the client sound system. There is no reason to grade this effort since the students would know by listening whether their ear worked or not.

Software for a "scenario design tool" allows the engineers to combine the ear simulation, simulations of measurement tools and other equipment developed for engineering courses, and create the assignment. They use the tool to give the assignment to a group of students, with a designated team leader. The students would divide up the problem (mechanics of the tympanic membrane and cavity, mechanics of Cochlear fluid flow, the sensors, electrical processing) and design and test their artificial ear.

The design tool also allows connecting a student and group monitoring system to the assignment. This allows tracking of individual students and the group as a whole. A student puzzled about something can ask a question and be directed to the appropriate tutorial from the anatomy class, FAQs, web-based resources, or to a human tutor available online 24x7 when appropriate. The engineers designing the course set parameters to suggest when the student or the group is getting lost or frustrated (too much time on a task, repetitive attempts and failures, or if they are making a mistake that earlier groups have made). These trigger interventions by a master simulation as well as the instructors. An instructor may be working at her desk when on call, and be alerted to a problem through a message. She opens the message and gets a quick snapshot of where the team is in the assignment. She can also replay their actions and construction attempts, review the questions they've asked earlier, and get advice from an AI-based system about how to provide answers. The students see her as an avatar wandering up to their construction site and offering advice. If she's stumped, she can call in an expert. The expert seeing the student's work can (a) provide detailed suggestions or (b) urge them to sign a non-disclosure statement and join her in a startup.

In addition to making it easy to design this complex "learn by doing" course component, the design tool would do all the record keeping. It would note each student's participation and achievements, it would insure payments to the developers of the ear simulation, it would dispatch questions to experts and pay them appropriately, and it would accumulate detailed information about each student's strengths, weaknesses, and preferences as revealed by the way he or she attacks problems and searches for information. The record would, therefore, include both transactional data for formal transcripts and commercial records, and it would include highly personal records about students that would be tightly protected and available only to selected individuals (teacher, the students themselves) or automated systems when privacy could be protected.

Research

While nothing in this scenario is impossible, intense research is needed to make it a reality; nothing approaching this kind of instruction is possible today:

- Building a simulated ear from components that pass mechanical, electrical, chemical, and other signals to each other and can be seen as functioning three dimensional objects at different scales requires fundamental developments in software design and object communication.
- The engineering teachers wanted to use simulated measuring instruments they had developed on an ear simulation developed in the medical school, this requires detailed standards and open architectures that don't exist.
- Tools to build an exploration-based, goal oriented scenario don't exist.
- Systems for parsing student questions and dispatching them as appropriate to pre-stored materials and tutorials or to human instructors don't exist.
- It would be difficult for the engineers to know whether this type of assignment would be best given to a group or to individuals (perhaps some individuals would work well in a group for this assignment but not others).
- Systems and metrics for tracking individual or group behavior and performance during and after the exercise don't exist. Developing generic tools that can be used for a wide range of assignments and collect information into a common format will be extraordinarily difficult.
- While instructional management systems exist today, nothing approaches the capabilities needed to support the system just described.