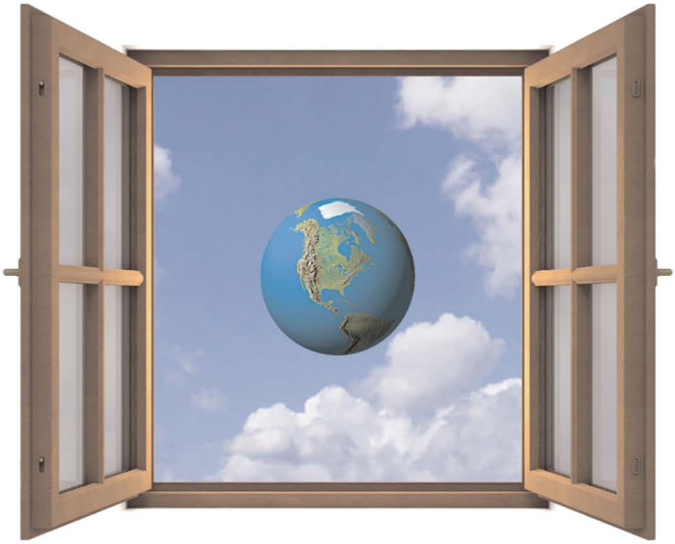
OPENING UP EDUCATION

The Collective Advancement of Education through Open Technology, Open Content, and Open Knowledge



edited by

Toru Iiyoshi and M. S. Vijay Kumar

foreword by John Seely Brown

Opening Up Education

Opening Up Education

The Collective Advancement of Education through Open Technology, Open Content, and Open Knowledge

Edited by
Toru Iiyoshi and M. S. Vijay Kumar

Foreword by John Seely Brown

The Carnegie Foundation for the Advancement of Teaching

The MIT Press
Cambridge, Massachusetts
London, England

This Creative Commons Edition is available through the generous support of the Carnegie Foundation for the Advancement of Teaching.

For information about special quantity discounts, please email special_sales@mitpress.mit.edu

This book was set in Sabon by SNP Best-set Typesetter Ltd., Hong Kong.

Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Opening up education : the collective advancement of education through open technology, open content, and open knowledge / edited by Toru Iiyoshi and M. S. Vijay Kumar.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-262-03371-8 (hardcover : alk. paper)
1. Distance education—Computer-assisted instruction. 2. Education, Higher—Effect of technological innovations on. 3. Educational technology. 4. Open learning. I. Iiyoshi, Toru. II. Kumar, M. S. Vijay.
LC5800.O678 2008
378.1′758—dc22

2007039375

10 9 8 7 6 5 4 3 2 1

To our wives and sons—
Hiromi, Rukmini, Ken, Suhas, and Taku
—whose support and encouragement makes this important work possible.

11

Building Open Learning as a Community-Based Research Activity

Candace Thille

Improvement in postsecondary education will require converting teaching from a "solo sport" to a community-based research activity.
—Herbert Simon (1998)

The open educational resources (OER) movement has the potential to provide broader access to higher education and to markedly improve the quality of higher education for a diverse body of learners. Many OER projects to date have focused on making content that supports existing traditional forms of instruction openly and freely available. In these projects, the power of the Internet is used to overcome barriers to access by serving as a medium for freely distributing content. Making existing content available in this way is based on the revolutionary idea that education and discovery are best advanced when knowledge is shared openly. These OER projects have enabled a great leap forward in democratizing access to educational material. The next step in the *revolutionary* potential of the OER movement is in using technology to make *instruction*, as well as materials, accessible to the widest possible audience of learners and, at the same time, *improve* teaching and learning.

The Challenge of Meeting the Growing Demand for Quality Higher Education

Pressures of many kinds grow in both the developed and, especially, the developing world to provide more people with increased access to education (United Nations Educational, Scientific and Cultural Organization [UNESCO]-World Bank, 2000). At the same time, report after report announces that the quality of education, even in the developed world, is not keeping pace with the demands of what is now and what will be an increasingly knowledge-based economy (Desjardins, Rubenson, and Milana, 2006; The National Academy of Sciences, 2007; President's Information Technology Advisory Committee, 2005; President's Council of Advisors on Science and Technology, 2004).

Traditional forms of developing and delivering instruction do not scale well to meet the growing demand. Individual faculty members working as solo practitioners who are experts in a domain of knowledge are often ill-equipped to address this changing context. A long-standing concern of many who have worked in higher education is that most faculty members' knowledge of how students learn is not only insufficient but also largely intuitive (Smith and Thille, 2004). Most faculty members are dedicated instructors and spend much time and energy preparing for their course presentations. In traditional teaching this meant spending hours reading and rereading books and articles, writing and rewriting lecture notes, anticipating student questions and formulating answers.

Historically, one of the fundamental errors in this process has been that faculty members often equate their own learning processes with their students' learning processes. Unfortunately, research has shown that as teachers become more expert in any discipline, they are less capable of seeing and understanding the difficulties encountered by the novice learner. This well-documented phenomenon of the "expert's blind spot" tells us that instructional intuitions of experts can be faulty, because expertise in a domain can cloud judgment about what is difficult for novice learners in that domain (Nathan and Koedinger, 2000). In traditional small-scale, face-to-face instruction with a fairly homogeneous student population, the problem of the expert's blind spot is sufficiently mitigated by the dynamic feedback that the instructor receives from students through the instructor's observations in class and through student questions.

In an open online environment, the dynamic feedback loops that mitigate the problem of the expert's blind spot are no longer present. In developing instruction for a diverse population of novice learners in these environments, it becomes critical that content experts not rely exclusively on their individual experiences and intuitions about learning. These challenges led Open Learning Initiative (OLI) to undertake a community-based research approach to course development.

A Research-Based Approach to OER Development

The fundamental goal of OLI is to develop Web-based learning environments that are the *complete enactment* of instruction. Our focus on designing and evaluating the *enactment of instruction* elucidates some of the opportunities, challenges, and implications of open educational resources for transforming education.

Our research is part of an effort to (a) develop better resources and practices, (b) include cycles of evaluation and improvement of resources and practices that are developed, and (c) contribute to advancing fundamental understanding, in this case, of learning. We develop courses and conduct studies designed to provide feedback for improving the courses and also to develop and evaluate hypotheses about the kinds of learning that occur.

At the beginning of an OLI course design, we investigate the learning challenges particular to the domain through literature reviews, analysis of artifacts of learning, or observational studies. Our team of faculty content experts, learning scientists, and software engineers then explore how best to use the benefits of the technology and the research from the learning sciences to design an environment to address these challenges. The design is then tested and evaluated through actual student use. OLI courses are guided by principles from current cognitive and learning theory and each course attempts to reflect in honest and authentic ways the core epistemic structure of the domain it represents.

For example, a challenge in chemistry education is that students can be quite proficient at solving the mathematical problems in chemistry textbooks without being able to flexibly apply those tools to novel chemistry phenomena in which their application would be useful. Prior to designing our course, we observed that students typically solve traditional chemistry textbook problems via a shallow ends-means analysis, by matching the information given in the problem statement with the equations they can pull from the chapter text.

To address this and other issues in chemistry education, rather than the traditional approach of teaching the abstract mathematical skills of chemistry out of context, the OLI chemistry course situates the learning in an authentic investigation that addresses real-world applications and asks students to approach chemistry problems as a chemist would approach them (Evans, Karabinos, Leinhardt, and Yaron, 2006). The OLI chemistry unit on stoichiometry is situated in a real-world problem of arsenic contamination of the water supply in Bangladesh.

Many of the course activities take place in the virtual chemistry lab, which provides opportunities for students to interact with the environment by exploring and manipulating objects, grappling with questions and designing experiments. This approach promotes deeper learning and lets students solve problems in different ways.

An analysis of the data logs of student use from a study conducted on the OLI stoichiometry course revealed that the number of engaged actions with the virtual lab not only matters, it matters a lot, explaining about 48 percent of the variation observed in the post-test scores for students taking OLI. The number of interactions with the virtual lab outweighed all other factors including gender and SAT score as the predictor of positive learning outcome (Evans, Yaron, and Leinhardt, 2007). The virtual lab activities are connected to computer-based mini-tutors so that students may ask for hints as they design experiments and get immediate targeted feedback on the results.

The computer-based OLI mini-tutors are derivations of the extensive work on cognitive tutors that was conducted for more than a decade at Carnegie Mellon (Koedinger and Anderson, 1993; Anderson, Corbett, Koedinger, and Pelletier, 1995; Koedinger, Anderson, Hadley, and Mark, 1997). The OLI mini-tutors behave in a similar fashion to cognitive tutors and to human tutors: making comments when the student errs, answering questions about what to do next, and maintaining a low profile when the student is performing well. The mini-tutors are grounded in studies that have attributed sizeable learning gains that students achieve with tutors to the targeted and immediate feedback given by tutors in the problem-solving context (Butler and Winne, 1995; Corbett and Anderson, 2001; Bransford, Brown, and Cocking, 2004).

The project's research activity begins with the initial design of the course and continues through implementation. During the design process and during use, the courses are continually evaluated through studies of student use and learning. All student learning activities in OLI courses and labs are, with the student's permission, digitally recorded in considerable detail to monitor student activity and capture the data required by such studies. The results of this built-in research inform the next iteration of the course. The research results also contribute back to the underlying design principle or learning theory.

Quality Web-based open learning resources can do more to realize the use of effective strategies from the learning sciences than other methods of delivery. OER courses can instantiate effective designs without requiring the faculty who are using the courses to develop expertise in the learning sciences. The students using the materials benefit from applications of strategies about which the instructor might have no knowledge. The instructors using the materials to support their teaching benefit from the information the system can give them about which areas their students are mastering and in which areas their students need additional instruction and support.

Developing a Community of Practice

The community engaged in this OLI research activity was originally composed of cognitive scientists, learning scientists, experts in human computer interaction, software engineers, faculty content experts, and learners mostly in the Pittsburgh area. As the project has developed, the community has expanded to include learning scientists, technical experts, and content experts from different kinds of institutions in the United States and several other nations. This expansion facilitates the development of new courses and contributes to an understanding of how the course materials and course contexts need to be adapted to be effective in diverse settings. It also raises new challenges for developing the best processes for engaging a larger community of research, use, reuse, adaptation, creation, and practice.

Through the open education movement, we have the potential to create a community of instructors, learning scientists, instructional support specialists, and others who strive together to make open learning as effective as it can be by studying how people learn and by engaging in use-driven design processes. OLI exemplifies the creation of such a community on a small scale. OLI faculty members remain engaged in the project because they have the opportunity to redefine what to teach and how to teach their domain in light of the benefits of the technology and the information from the learning sciences. The effort has produced a community of scholars from diverse disciplines who are also committed to scientifically based, online teaching as a path to improving quality and access to instruction.

The process is intensely reflexive. Our challenge now lies in extending this enthusiasm and process to an even larger community. In spite of our lack of promotion of the approach, participating in such a community has already captured the imagination of faculty at institutions in several countries. Faculty from institutions in Chile, Columbia, India, Mexico, Qatar, and Taiwan are currently collaborating with us in using, evaluating, and extending OLI courses or in developing new OLI courses. The nature of the relationship varies by institution and course area. At Qatar University (QU), the statistics faculty is collaborating with OLI to develop alternative and additional data-analysis examples that are more culturally appropriate. The QU biology faculty members are using and evaluating the OLI biology course material and actively working with the Carnegie Mellon biology faculty members to extend the material. In Colombia, the department of psychology at Universidad de los Andes implemented and formally evaluated a blend of the material from the OLI statistics course and the OLI causal reasoning course. In Taiwan, faculty members and technical staff from National Chiao Tung University (NCTU) attended the OLI developers' workshop at Carnegie Mellon and have since installed an OLI appliance (a fully configured server with the OLI development and delivery environment and all the course content), hosted an OLI technical workshop at NCTU, and are actively developing a calculus course in Chinese. OLI is now collaborating with NCTU on development of the calculus course and will work with NCTU to translate the course into English rather than continuing development on our own calculus course.

The Challenge of Use and Reuse

Some of the OER's greatest challenges are in the area of use and reuse. The OER movement has successfully facilitated the production of a large amount of open content. Deliberate efforts to create diverse kinds of high quality open educational resources for different purposes and audiences have arisen in the last six or seven years. These efforts are changing the Internet as an educational resource in several ways and are increasing the amount and diversity of quality educational resources that can be found (Atkins, Brown, and Hammond, 2007).

In the OER movement, instructors have expressed the desire to create, reuse, and remix resources to better fit their teaching approaches and the needs of their students. Instructors who create, use, reuse, and remix OERs possess different levels of expertise, interest, time, and resources to select, organize, adapt, and create material. Some instructors have a clear idea of what material to include and how to organize it so they can create a flow that they believe will work best for their students. These instructors are more likely to want modular materials that they can adapt and fit into their own design. Other instructors seek a well-tested collection and organization of material that they can adopt and teach. The challenge in reuse and remix of OER courses and course components is in addressing these diverse needs and abilities of instructors while still maintaining the quality of the OER for the learner.

Some challenges to reuse and remix are technological. Standards bodies provide a forum for building agreement on standards of interoperability. For example, the International Organization for Standardization (ISO; See www.iso.org) is making Sharable Content Object Reference Model (SCORM) a standard. The Sakai organization (See http://sakaiproject.org) has participating members from many institutions. The IMS Global Learning Consortium (See www.imsglobal.org) has representatives from industry and educational institutions. OKI Open Service Interface Definitions (OSID; See www.okiproject.org) have gained considerable attention and compliance by a number of online educational tools, encouraging service-oriented architectures that promote interoperability. While many projects try to instantiate these standards, there are challenges. OERs are of different types, are intended to meet diverse needs, and are developed and used by audiences with varying levels of technical expertise and resources. This diversity accentuates some challenges of standardization, such as complexity of standards, cost and difficulty in implementing standards, grain-size issues with content aggregation, and less-than-perfect interoperability even when one adheres to standards. Developers often perceive adhering to a standard as both limiting what an individual can do and as imposing requirements that the individual does not perceive as related to his or her work.

The need for standardization and interoperability has become more critical as users with little technical expertise attempt to assemble components built from vastly different technologies. This is especially true when the goal is to physically move, assemble, and deliver diverse OERs from a single location or when the goal is to leverage common middleware and data stores. It is the right goal; it remains challenging to achieve.

An interim and low-cost approach might be to virtually assemble OERs through links on the Web. One can link to a resource on a remote server to include it in an educational intervention rather than actually having to move the resource into a local environment. If a sequence of diverse OERs that have been virtually assembled in this way are to be used for credit-granting purposes, then the areas in which interoperability are most critical are in areas of authentication and reporting. Shibboleth (See http://shibboleth.internet2.edu/) is designed to leverage each institution's authentication strategy to create a trust fabric. Using the trust fabric, an instructor could virtually assemble a sequence of OERs and direct his or her students to follow a sequence of links. The students would be able to seamlessly follow the sequence without having to authenticate at each server, and the students' work from the diverse servers would be reported back to the instructor.

The technological challenges may well be easier to overcome than the greater challenge of creating a self-sustaining ecology in which members are active participants not only in production, adaptation, and consumption of learning resources but also in reflection and evaluation. As described above, we have had successes in facilitating reuse and extensions to the OLI courses with our partners at other institutions both in the United States and abroad, but the efforts are time- and labor-intensive and do not scale easily.

Several projects in the OER movement have taken an alternate approach to supporting reuse and remix. The Connexions (See http://cnx.org/) project provides tools and environments that support teachers and others to author, share, select, remix, mash-up, and deliver OERs without the need for direct collaboration with the original authors. In addition to making some very good content available, Connexions has done excellent work in developing an environment and tools to support faculty to author, mash-up, and remix content to support their teaching. Faculty with little or no technical expertise can author original materials and courses and also modify and extend existing materials and courses that others have created. Connexions has also made it very easy for faculty to take the original material or the mashed-up and remixed material and deliver it as a textbook. In spite of this focus and the development of the easy-to-use tool set, there are still very few examples of faculty members who were not involved in the original development of the courses who have taken a course developed by someone else, made significant changes, adaptations, and/or extensions that they used in their teaching, and then contributed their adaptation back to the collection. A recent study has suggested that a key barrier to faculty adopting and adapting others' innovations into their teaching is the scant preparation, help, and reward that typical faculty receive for continually updating and improving their courses (Ehrmann, Gilbert, and McMartin, 2007).

The Knowledge Media Lab (KML) at The Carnegie Foundation for the Advancement of Teaching has been investigating how to support educators and students in documenting, sharing, and building knowledge of effective practices and successful educational resources to collectively advance teaching and learning for some time. OER projects are using the KEEP Toolkit developed by the KML to document and communicate both the original design rationale and the many variations on contextual use of the OER courses (Iiyoshi, Richardson, and McGrath, 2006). In the OLI project, course development teams complete the KEEP OLI author template to document and communicate the instructional goals and learning theory that guide course development. Instructors at a variety of institutions who are using OLI courses complete the KEEP OLI user template to document and communicate a description of the context in which the online courses are delivered and the impact of using the OLI course on teaching and learning. The combination of the KEEP OLI author document and the collection of the KEEP OLI user documents for each course provide potential users with an understanding of the logic and goals behind each course and with rich information about the institutional, sociocultural, and curricular contexts of teaching and learning.

In addition to the case study-type documentation that OLI and other projects are creating using the KEEP Toolkit, perhaps we need a schema by which authors and instructors can tag their resource, or their remix of another's resource, with references to the following: the context in which the resource has been used effectively, and either the learning principles that underlie its design or an evaluation validating the effectiveness of the resource or remix. At minimum, we need a common terminology that describes different types of OERs so that members can more easily find resources and audiences that meet their needs.

OERs Supporting Instructors to Improve Teaching and Learning

The initial motivation of the OLI was to develop exemplars of high quality, online courses that support individual learners in achieving the same learning goals as students enrolled in similar courses at Carnegie Mellon University. Although originally designed to support individual learners, OLI courses are increasingly used by instructors inside and outside of Carnegie Mellon as a complement to their instructor-led courses to address the challenges they confront due to the increasing variability in their students' background knowledge, relevant skills, and future goals.

Creating an effective feedback loop to instructors using the OLI courses is our current area of investigation. The process goes something like this: The instructor assigns students to work through a segment of the online instruction. The system collects data as the students work. The system automatically analyzes and organizes the data to present the instructor with the students' current "learning state." The instructor reviews the information and adapts instruction accordingly. The richness of the data we are collecting about student use and learning provides an unprecedented opportunity for keeping instructors in tune with the many aspects of students' learning.

An interesting result of the OLI involves the effects of this kind of effort on the community of faculty engaged in the project. While a high level of commitment existed from the beginning, the nature of the commitment changed over the course of the project. Initially, the participation of many faculty and departments was motivated by a desire to share expertise and knowledge with the world—much the same motivation of OpenCourseWare projects. Some faculty members were also motivated by a curiosity to explore how critical aspects of their domain could be taught effectively in an online medium. Most faculty and departments did not initially consider using the OLI courses at Carnegie Mellon. As the OLI courses were originally intended and developed to be generally used by a wide range of faculty and students at various institutions, as well as self-learners, some faculty members were concerned that OLI course materials might not be specialized enough to improve current instruction, especially given Carnegie Mellon's specific needs and high-level goals for teaching and learning. Many also held the belief that an online learning environment would always be inferior to a classroom with a human instructor.

It is now the case that almost all OLI courses, or major components of them, are used in Carnegie Mellon courses. We now receive requests from faculty and departments to "put their courses in OLI." Faculty members hear from their colleagues about the impact of OLI courses, and they contact us to explore how to create an OLI environment in their domain to address student learning challenges. Another unanticipated benefit is that faculty members involved in the project have improved the way they teach traditional courses based on what they learned in the OLI course development process. At the beginning of the process, we insist that faculty clearly articulate the learning objectives as observable student-centered measures and then work with the development teams to construct learning activities and assessment that align with the stated objectives. Articulating student-centered measurable learning objectives is often the hardest part of the process for faculty.

Evaluation of Open Educational Resources

Sustaining an open education movement requires a demonstration of effectiveness. More studies of impact of OERs are needed. Much of the data remains anecdotal. The careful studies have yielded hopeful results, but in the end, data about the value of the efforts is part of maintaining the current high level of enthusiasm.

A major goal of the OLI is to provide access to high quality postsecondary courses (similar to those taught at Carnegie Mellon) to learners who cannot attend such institutions. OLI course design has been guided by principles of learning theory that stress the importance of interactive environments, feedback on student understanding and performance, authentic problem solving, and efficient computer interfaces. The expectation of high educational quality in these courses stems from close collaboration throughout the development of the OLI courses among cognitive scientists, experts in human-computer interaction, and experienced faculty who have both deep expertise in their respective fields and a strong commitment to excellence in teaching. Ensuring that these expectations are realized falls to the formative and summative evaluation strategies that are built into OLI course-creation methods.

Our summative evaluation efforts to date have studied the degree to which we have achieved our goal in developing online courses that enact instruction at least as effectively as existing instructor-led courses. We have collected empirical information about the instructional effectiveness of OLI courses as stand-alone courses and in blended modes (online instruction supplemented by faculty instruction or tutoring) in contrast to traditional instruction.

The OLI's overall evaluation plan/approach has included several important components. First, there have been several analyses of the cognitive and pedagogical features of curricula currently offered by others in an online model. These reports are typically generated at the beginning of a course development effort to guide the course design. Second, there have been a number of formative assessments and usability and design studies. These reports are generated throughout the design process and guide us in the revision and retooling of course components. Third, there have been a number of learning and effectiveness studies that use randomized controls or ABAB designs that have pointed to the comparability of OLI courses and face-to-face courses. The array of studies has produced an *Evaluative Portfolio* for OLI work that appears on the OLI Web site. We have discovered that our courses have the potential not only to do as well as traditional instruction in supporting students to achieve learning outcomes, but also to improve instruction and learning beyond traditional levels.

Our current studies focus on the *accelerated learning hypothesis*: that an individual can learn more material in a shorter amount of time with equal learning gains for each topic covered. We seek to demonstrate accelerated learning by showing that a learner can complete a semester-long course in significantly less than a semester and/or that a learner can complete significantly more than a semester's worth of material within a semester's time. In both cases, we are assessing students to ensure that the OLI and traditional groups demonstrate similar learning outcomes on the core material. The first accelerated learning study demonstrated that students using the OLI statistics course could complete the course in 8 weeks with two class meetings per week compared to the students in the traditional control condition who completed the same course in 15 weeks with four class meetings per week. Students in the accelerated OLI and traditional conditions spent the same amount of time in a given week on statistics outside of class. The OLI accelerated students demonstrated significantly greater learning gains than the traditional controls, and there was no significant difference in retention between the two groups in tests given 4 to 6 months later (Lovett and Thille, 2007).

Conclusion

Ultimately, it is not the technology itself but rather the new practices and communities that the technology enables that will revolutionize postsecondary education. In the case of OERs, the technology, the communities, and practices that develop around the OERs may ultimately allow us to close the feedback loop and support institutions of higher learning to become learning institutions.

References

Anderson, J. R., Corbett, A. T., Koedinger, K. R., and Pelletier, R. (1995). Cognitive tutors: Lessons learned. *Journal of the Learning Sciences*, 4(2), 167–207.

Atkins, D., Brown, J. S., and Hammond, L. (2007). *A Review of the Open Educational Resources (OER) Movement: Achievements, Challenges, and New Opportunities*. [A publication of The William and Flora Hewlett Foundation]. Retrieved March 23, 2007, from http://www.hewlett.org/Programs/Education/OER/OpenContent/Hewlett+OER+Report.htm

Bransford, J. D., Brown, A. L., and Cocking, R. R. (Eds.). (2004). *How people learn: Brain, mind, experience, and school*. [Expanded edition]. Washington, DC: National Academy Press.

Butler, D. L., and Winne, P. H. (1995). Feedback and self-regulated learning: A theoretical synthesis. *Review of Educational Research*, 65, 245–281.

Corbett, A. T., and Anderson, J. R. (2001). Locus of feedback control in computer-based tutoring: Impact on learning rate, achievement and attitudes. Proceedings of the Association for Computing Machinery 2001 CHI conference, held in Seattle, WA, from March 31–April 5, 2001.

Desjardins, R., Rubenson, K., and Milana, M. (2006). Unequal chances to participate in adult learning: International perspectives. Paris: UNESCO International Institute for Educational Planning. *Fundamentals of Educational Planning*, 83.

Evans, K., Karabinos, M., Leinhardt, G., and Yaron, D. (2006, April). Chemistry in the field and chemistry in the classroom: A cognitive disconnect? *Journal of Chemical Education*, 83(4), 655.

Evans, K., Yaron, D., and Leinhardt, G. (in press). Learning stoichiometry: A comparison of text and multimedia formats. *Chemistry Education: Research Practice*. Mercyhurst College, Education Department; Carnegie Mellon University, Department of Chemistry: Pittsburgh, PA; University of Pittsburgh, Learning Research and Development Center, Pittsburgh, PA.

Ehrmann, S. C., Gilbert, S. W., and McMartin, F. (2007). *Factors Affecting the Adoption of Faculty-Developed Academic Software: A Study of Five iCampus Projects*. Takoma, MD: The TLT Group.

Iiyoshi, T., Richardson, C., and McGrath, O. (2006, October/November). Harnessing open technologies to promote open educational knowledge sharing. *Innovate*, 3(1). Retrieved May 15, 2007, from www.innovateonline.info.

Koedinger, K. R., and Anderson, J. R. (1993). Reifying implicit planning in geometry: Guidelines for model-based intelligent tutoring system design. In S. Lajoie and S. Derry (Eds.), *Computers as Cognitive Tools*. Hillsdale, NJ: Erlbaum.

Koedinger, K. R., Anderson, J. R., Hadley, W. H., and Mark, M. A. (1997). Intelligent tutoring goes to school in the big city. *International Journal of Artificial Intelligence in Education*, 8, 30–43.

Lovett, M., and Thille, C. (2007). Measuring the effectiveness of OLI statistics course in accelerating learning. Milton Keynes: Proceedings of OpenLearn2007.

Nathan, M. J., and Koedinger, K. R. (2000). Teachers' and researchers' beliefs of early algebra development. *Journal of Mathematics Education Research*, 31(2), 168–190.

National Academy of Sciences Committee on Science, Engineering and Public Policy. (2007). *Rising above the gathering storm: Energizing and employing America for a brighter economic future*. Washington, DC: The National Academies Press.

President's Information Technology Advisory Committee. (2005). *Computational science: Ensuring America's competitiveness*. Arlington, VA: National Coordination Office for Research and Development.

President's Council of Advisors on Science and Technology, Workforce/Education Subcommittee. (2004). *Sustaining the Nation's Innovation Ecosystems, Information Technology Manufacturing and Competitiveness*. [Report approved at full President's Council of Advisors on Science and Technology meeting on December 3, 2003.] Washington, DC.

Simon, Herbert. (1998). Teaching: Need it be a solo sport? Delivered at Last Lecture Series, Carnegie Mellon University, Pittsburgh, PA. [Videorecording].

Smith, J. M., and Thille, C. (2004). *The Open Learning Initiative: Cognitively Informed e-Learning*. London: The Observatory on Borderless Higher Education.

United Nations Educational, Scientific and Cultural Organization—World Bank. (2000). *Higher Education in Developing Countries: Peril or Promise*. Washington, DC: The Task Force on Higher Education and Society.