INFORMATION TECHNOLOGY RESEARCH AND EDUCATION, TEACHING, AND LEARNING

REPORT ON TWO NSF-FUNDED WORKSHOPS

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Preface

With support from the Experimental and Integrative Activities Division (EIA) of the Computer and Information Science and Engineering Directorate (CISE) of the National Science Foundation (NSF), SRI International conducted two invitational meetings whose objective was an in-depth discussion of research issues at the interface of information technology and learning science research. The first meeting was organized by Dr. Nora Sabelli and took place March 4-6, 2002, at the Rickeys Hyatt Hotel in Palo Alto, California. The second meeting was organized by Dr. Chris DiGiano and took place July 16-18, 2003, at the Centennial Hotel in Boulder, Colorado.

The meetings consisted of a series of panel discussions on topics suggested by awards made by the Information Technology Research (ITR) Initiative. The awards were chosen by the workshop organizers for coherence around special topics and for relevance to learning research and to education. Participants were members of the learning sciences research community who had worked extensively with technology and computer science researchers with direct connections to learning sciences and education. Three parallel objectives drove the selection of invitees: (1) to produce a series of commentaries that EIA will be able to use in conversations with proposers and principal investigators, (2) to seed an expanded collaborative community of researchers, and (3) to identify promising new program areas for NSF. Since the organizers expected that there would be other meetings where different aspects of information technology and learning sciences would be explored, the list of invitees was kept small to encourage open discussions and no attempt was made to be entirely inclusive.

The first workshop focused on research and implementation of learning technologies and prepared programmatic recommendations to NSF in support of areas of promising and high priority learning technology research. A report on the workshop was submitted to EIA in 2002. Participants included established ITR researchers, young investigators, other learning sciences senior researchers, and several interested observers. The second workshop focused on software engineering, training programs, and the implementation of learning technologies as they relate to the professional preparation of learning technology specialists. Specific recommendations to NSF were outlined in a report submitted to EIA in 2003.

The present report provides an overview of both sets of recommendations aggregated in a systematic fashion. The objective is to provide a monograph that can be widely distributed in the field to spur further discussions.

Participants in each workshop reviewed the individual workshop drafts. The Editors wish to thank all the ITR PIs who contributed to the workshops and those who expressed strong interest but were unable to attend. Additional thanks are due to Kenneth Whang, NSF Program Officer, for his participation, suggestions, and encouragement. This report should be considered a work in progress, and the editors solicit comments and proposed enhancements.

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Nora Sabelli and Chris DiGiano
Menlo Park, California and Boulder, Colorado, April 2004

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Background

Fulfilling the potential that information technology (IT) offers education requires that attention be paid simultaneously to advances in technology and to knowledge of how people learn with technology. Absent these two complementary aspects, IT use in educational contexts will be marginalized and will not achieve its full transformative[1] potential.

Successful interdisciplinary research benefits from venues where researchers from distinct disciplinary traditions come together and explore the most promising facets of a common problem. In this vein, EIA funded meetings of ITR and learning science researchers to explore what learning research questions have become possible to investigate on the basis of current ITR and computer science research and to encourage cross-fertilization of the fields. The projects represented by these researchers include, but go beyond, those identified as belonging to the Education, Training and Workforce (ETW) strand of ITR; they include studies of problems such as visual representations and access to remote experimental equipment.

The current emphasis on high-stakes testing and accountability brings about pressures to consider education as it is, not to create new and more powerful visions of education, which is an important consideration for ITR and learning science research. Without a proactive effort, the time it will take the respective communities to learn about each other's work will be too long, and a delay will not serve the country well. We need to bring to interested members of the ITR community information on the knowledge, needs, and constraints of education and learning, and to learning science researchers the ideas and potentials of current computer science research. This is a task for NSF. Cross-fertilization is fundamental, given the importance of advances in these fields to the economic and scientific well-being of the country and the consequent need to shorten the time frame for education and learning to take advantage of fast-moving technological advances.

The project funded two workshops. The first (hereafter referred to as the "research workshop") was of a general nature and brought together members of the ITR community interested or working in learning and education, and learning science researchers working with technology. A second workshop (hereafter referred to as the "training and implementation workshop") focused more specifically on the education of learning technologies practitioners and included a consideration of the conditions for successful practical implementation of learning technologies research outcomes. The participants in this training and implementation workshop were learning technology researchers already engaged in both technology and education research and teaching. This workshop was able to provide specific recommendations for those interested in educating the next generation of technologists and those using or implementing these technologies in schools.

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[1] The word transformative here indicates uses of technology that foster and support pedagogical transformations, based on education research and the affordances of technology. It is contrasted here with enhancements to existing teaching and learning practice. Transformations may be in the complexity of concepts taught, the education level at which these concepts are introduced, or the number of students attracted to continued studies and Science, Technology, Engineering and Mathematics (STEM) professional careers.

Human capacity building and the need for a strong group of researchers who can function at the interface between fields is a critical issue for the future of learning sciences and permeated discussions at both workshops. Programming languages, approaches, and deployment practices differ between disciplines and between the communities involved. Discussions made it very clear that even research of the highest quality suffers when knowledge about either the learning application domain or the evolution of technology is limited to that available in the published literature.

Prior NSF-funded meetings in the learning sciences dealt with the theoretical and developmental underpinnings of innovative, leading edge, collaborative research on issues of learning and technology. Two such workshops can be considered precursors to the work reported here. Mark Guzdial of Georgia Tech and Rick Weingarten of the Computing Research Association (CRA) organized a workshop which led to a solicitation for an interdisciplinary NSF program called Collaborative Research on Learning Technologies (CRLT, 1995).[2] NSF organized a workshop in 1995, which led to a program solicitation for Learning and Intelligent Systems (LIS).[3]

The purpose of the present report is to inform the larger ITR community about promising areas of collaboration around pressing learning science problems, including the preparation of future professionals. NSF has a critical role to play in stimulating the advances called for in the workshops by bringing together researchers and by providing the conditions under which their joint work can fruitfully take place—truly collaborative work requires additional human and monetary resources over that conducted by individual principal investigators. It also must be subject to stringent but multidisciplinary peer and merit review, yet conducted in such a way that high-risk, high-gain projects can be supported.

For the work reported here, meetings were organized around themes, with discussions allowed to flow freely and range widely. The themes, shown below, were chosen after the workshop organizers reviewed all ITR awards.[4] Those whose main focus was directly related to learning or that were principally implementation or development without research were not considered for the research workshop, but were included in the pool for the training and implementation workshop.

Themes for workshop I ("research")

- Visualizations, simulations, and immersive technologies

- Web-based distance learning

- Embedding assessment strategies and analyzing student data

- Cultural, cognitive, and social dynamics

- Virtual laboratories and remote instrumentation

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[2] Available at http://www.cc.gatech.edu/gvu/edtech/nsfws
[3] Available by request from CTL
[4] All awards were considered, not only those in the Education, Training and Workforce strand of ITR.

Themes for workshop II ("training and implementation")

- Design engineering issues in learning technologies

- Preparing professionals for learning technology design

- Putting the lessons to work: implementation and impact.

The remainder of this report is organized as follows. First, we discuss the links between learning research, education, and information technologies. Next, we describe promising areas of research at the intersection of IT and learning sciences research, as discussed by the research workshop. Then we describe programmatic and capacity-building considerations for future programs, as discussed by the education and training workshop. We then describe promising research thrusts in integrating technology and learning sciences, and briefly outline key problems and recommended strategies in IT and education research.

In the final section, we describe our recommendations on the education and training of the future professionals in the learning technologies field.

Links between Research, Learning, Education, and Information Technologies

In this section, we address the often overlooked role of research in educational change. Traditional concepts of education are being transformed by technology, changing learner demographics, and social needs. Until recently, education was characterized as a centrally-organized knowledge transmission system. However, modern views of the field emphasize a complex interplay of the distinct notions of "learning," "teaching," and "education." This separation, enabled to a significant degree by the customization allowed by information technology, raises new questions, each with their own research opportunities. Many of these questions relate to the public role of education and necessitate the principled consideration of social science research aspects of technology R&D.

Attending to contextual issues identified by social science research has now become common practice in the design of new technologies and the policies that govern their use. This is complicated in interesting ways by the fact that a new technology tends to change its own context, resulting in a moving target. For example, in the physical sciences, computing has not only helped scientists conduct their research more effectively, but it has enabled whole new kinds of research that were previously impractical. Similarly, in education technology is allowing young students to explore subject areas never before considered for their age and enabling educators to teach in new ways because of the detailed student assessment data at their fingertips.

The field of "learning sciences" has emerged to make sense of the interaction between learning, teaching, and education and the technologies and other contextual factors that have the potential to radically transform them. However, progress in the learning sciences continues to be hindered, even if to only a limited degree, by a disconnect between research in education and research in technology. The 1997 report of the President's Committee of Advisors on Science and Technology[5] attributes this to meager R&D investments by the education private sector. It would seem that the potential scientific and education gains are being limited by artificial boundaries, both programmatic and disciplinary. However, the potential is great and should not be ignored. A sampling of the possible advances that result from crossing boundaries among disciplines and programs all supported by NSF were described in the 1995 NSF workshop[6] that led to the LIS solicitation:

> Recent advances in the study of human learning and reasoning have facilitated the design of learning environments, and also have suggested ways in which systems can be designed to productively organize the information in a complex environment. Processes such as abstraction, summarization, pattern recognition, sampling, and hierarchical categorization are necessary to interact with the vast amounts of information found in complex systems such as air traffic control, advanced manufacturing, instruction, or crisis management. In designing such

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[5] http://www.ostp.gov/PCAST/k-12ed.html
[6] Available upon request from CTL

complex systems, we can draw upon cognitive psychological research into the variety of learning processes used by human learners to deal with complexity—for example: implicit learning versus explicit learning; deductive versus inductive learning; analogical or case-based learning versus explanation-based learning; associative learning versus symbolic learning; and declarative learning versus compilation or routinization of learning. These different learning processes can be compared with computational learning methods developed by researchers in computer science, control theory, AI, and machine learning to suggest lines of research into human cognitive processes as well as ways of applying these processes within computational systems more generally.

NSF has a critical role to play in helping create the proper research and education conditions—including support for the researchers and students—for building an effective and efficient learning sciences research community

We introduce two diagrams to summarize the main conclusions of the two meetings. The rest of the document will address the considerations that led to the diagrams and will present specific recommendations. These recommendations are addressed to NSF, as a likely funder of the work, and to research colleagues who wish to explore the wisdom of the field regarding areas of emphasis.

Figure 1 presents a diagram of areas of overlap between the fields of learning, cognition, and computer science, which highlight the promising collaborations identified from the workshop discussions. The areas of overlap suggest some of the common problems and common vocabulary that could bring these two fields together. The implied collaborations can take place at many levels of aggregation, from theory to classroom research.

Figure 1. Overlapping Areas of Research

Learning and Cognition Areas		Computer Science Areas
Learning environments and tools	Infrastructure	Digital Libraries, Open Source, Devices
Interactivity, Manipulatives	Representational Systems	Collaboration Tools, Human-Computer Interaction, 3D graphics
Assessment, Tutoring	User Modeling	Knowledge-based systems, AI
Theory testing, Scale issues	Analysis	Data Mining, Distributed Computing

Figure 2 points to the conditions for successful adoption of learning technologies in a classroom, though the conditions apply to any successful adoption, not only to learning technology ones. These conditions speak directly to the breadth of topics required in the preparation of learning technologists.

The first condition, a *sinequanon*, is learning effectiveness—how well students learn through better teaching of important content—and highlights the role that learning sciences should play in learning technology R&D. A second condition, one that speaks to the effort required to use a technology effectively, is the efficiency of the technology (i.e., the time- and cost-effectiveness that comes out of good software engineering practices). Efficiency is directly related to good practices of design science and engineering in the process of development. The last one, the hardest to achieve but one that must be in place for sustained impact, is stability (continuous access to resources that comes from an appropriate human and technological infrastructure). Stability implies not only software robustness and ability to "break with grace" but an understanding of the infrastructure that must be in place for appropriate adoption and adaptation to proceed apace.
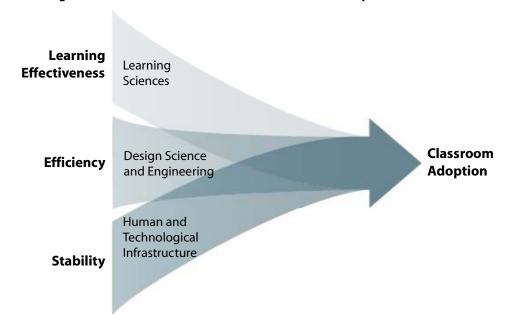
Figure 2. Preconditions for Successful Classroom Adoption

Learning Effectiveness — Learning Sciences

Efficiency — Design Science and Engineering

Stability — Human and Technological Infrastructure

Classroom Adoption

Research and education at the interface of it and learning sciences[7]

Both workshops reiterated the call for a research program that supports pedagogically transformative uses of technology. To accomplish this, information technology research must integrate thinking from the social sciences—not only cognitive science, but social theory, social networks, organizational theory, work practices, and critical theory perspectives. There is a need to bring to the fore new questions and methods that will

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[7] This section borrows from and builds on the LIS workshop report mentioned earlier and particularly its section on "Learning Mechanisms and the Learner" which provides the theoretical foundations of the present work. The arguments in that report are still valid, and experience indicates that the education- and human-oriented aspects of LIS still require continued attention and targeted support.

help clarify and address the "digital divide" and the cultural and gender issues that must be solved for successful deployment and use of technologies in learning throughout society. Though claims that culture has a direct effect on the adoption and use of technology make intuitive sense, more empirical work is essential. A critical question with direct implications for learning technology, for example, is how beliefs about identity influence what is learned by individuals in various contexts.

Participants expressed concerns about NSF's fomenting a culture of "education as outreach" in disciplinary programs, without a concomitant call for integrating lessons learned from the learning sciences. A learning sciences and technology program can help educate disciplinary programs about paying closer attention to what is known about making learning successful for more students. It was clear during the training and implementation deliberations that there is a significant difference between designing learning technologies and designing other kinds of technologies.

It is interesting to note that, when the discussions in the research workshop moved into conducting learning research in classrooms, it took on a clear engineering orientation consistent with researchers' and policy-makers' recent reflections on the link between research and practice in education.[8] The successful linkage is dependent on the learning environment, which includes the social and cultural context of learning and, of ever-increasing importance, engineered or "cognitive" artifacts.

There is ample research on specific types of learning and types of tools for supporting transformative learning. Yet our view of learning is currently fragmented, and the possible integration across projects—at a minimum, their aggregation into more encompassing environments—was a topic raised several times by participants and organizers. For example, how to combine "learning by explaining," "collaborative learning," "over-the-shoulder learning," etc., each with its own separate research and supporting software, is itself a topic for research. Such investigations could help define more comprehensive, supportive environments that integrate, for example, multiple representations and multiple modes of work. Without such integration, limited research resources will being spread across a wide variety of technical strategies and idiosyncratic tools.

Given the multitude of technological and pedagogical approaches that are being explored by researchers and the different demands that these approaches make on teachers, the overarching questions are:

1. What kind of subject matter is best taught with new technologies?

2. In what way should that content be taught?

3. What kinds of students should learn that content?

4. What is the cost in terms of teacher time and training?

5. How will effectiveness of learning be measured?

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[8] See the education case study titled "Basic Research in Service of Public Objectives" which is linked to from the page http://www.cspo.org/projects/enhancing/index.html

The workshop discussions indicated that the integration of existing research that looks at a subset of these questions—each one with its own importance for practice—has become possible and desirable. An effective decomposition of the research space and techniques for integrating the results would be a significant milestone for our field, warranting important changes in how we train future learning technologists.

General programmatic considerations

The research workshop brought up the importance of more theoretical, basic research such as the cognition underlying the understanding of learning with technology—leading to principles for the design of functional technology for education and for its integration into broader learning environments. This work requires collaboration between technology designers, subject matter experts, classroom faculty, and learning scientists.

Science in this field has arrived at a point at which many of the most complex, difficult, and potentially important research questions demand an interdisciplinary approach. Problems in learning (on the part of both humans and systems) are increasingly driving the organization of research teams. The challenge now (rather than approaching problems from within a particular disciplinary domain) is to focus instead on the overall nature of this new, difficult, but vital enterprise through a research initiative that can bring to bear the full arsenal of ideas and research methods that the various disciplines have to offer at the same time developing new ideas and methodologies.[9, 10]

The implications of this statement acquire additional meaning if we remember that the NSF programs that preceded the workshops (CRLT and LIS) were of short duration. Proposers will want to have specific information about funding paths before committing to the time and effort of collaborative research; specific questions that were raised by the research workshop discussions include:

- **The nature of the review process.** Will it be interdisciplinary? What disciplines will be included? Is the program interested in high-risk/high-gain research projects? Will support for interdisciplinary work and tolerance for risk be made clear to reviewers?

- **The expectations for funding levels.** Will the inclusion of several senior researchers, with concomitant levels of support, be considered a positive, negative, or neutral criterion for funding?

- **Program expectations for graduate and postdoctoral student support.** Given the need for building capacity for learning sciences research involving more advanced technology development, what support will be expected for capacity-building?

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[9] Available upon request to CTL

[10] Some overlap between programs housed in CISE, in SBE, and in EHR is important, not only to foster competing approaches to important problems but to minimize the danger that important work will fall through the cracks, which is currently the case. In fact, there is a conceptual link between these programs, with respect to the nature of the research question, the development of a solution, and the testing of the solution in large-scale applications

- ***The nature of the problems and of their link to classroom and other environments.*** Will the level of funding allow projects to move out of the lab into schools, to increase research efficiency and applicability of the results?

- ***The nature of NSF's interest.*** Is this a program that has possible buy-in from other parts of NSF, especially but not only the Education and Human Resources (HER) and Social, Behavorial, and Economic Sciences (SBE) Directorates?

Capacity-building considerations

The research workshop identified two important goals, which became a central topic of discussion in the 2nd workshop: (1) scaling up research to have a larger impact, and (2) facing the challenges of implementation in the field. Participants generally agreed that while core concepts in the learning sciences deserve continuing re-exploration in the context of educational technology *identifying new scaling and implementation research issues has to take place while reasserting old, basic, unanswered research questions.*

In the opinion of participants, NSF should consider how a call for research proposals should be written to promote research that allows for *effective scaling up during the project or upon its completion*. A call for classroom research would be a start, but going from the research classroom to the real classroom is not a simple step (see, for example, the NRC [2000] report *How People Learn*, expanded edition). Addressing interoperability issues with legacy and complementary technologies and developing rapid authoring tools would be very useful to achieve scaling, as would supporting design collaborations that include classroom practitioners, comparing the learning technology choices facing educators, and working with teachers who have not been involved in the development of the projects. Work on all these areas would benefit from coordination with the EHR programs. Cooperation between programs in the CISE (including infrastructure R&D), EHR, and SBE Directorates will help ensure that technology affordances are included in fundamental and relevant research and that learning needs are integrated into infrastructure development efficiently and effectively.

Workshop participants thus recommended that NSF fund a variety of projects and activities, including full-scale, multiyear collaborative implementation and research projects; fellowships and conferences; planning awards; exploratory, high-risk/high-payoff research; and aggregation centers. It is important that the development of software tools and their study in real environments be an integral part of these projects, and that funding strategies attempt to increase the rather small number of learning technology researchers that can function at the interface of technology and learning sciences.

Fellowships. Fellowships could be offered both to faculty (to support a senior faculty researcher in an endeavor to learn a new field) and postdoctoral and doctoral students (to join a working research group) each of which would provide training across disciplines. Support for colloquia and workshops aimed at facilitating interdisciplinary communication and exposure across areas can be an effective mechanism to encourage researchers to form collaborations before submitting proposals. The fundamental research carried out under such a program's funding can be transitioned to sustainable

real-world applications through programs such as Small Business Innovation Research and the Interagency Education Research Initiative (IERI), and we expect that NSF will see gains from increased coordination with these programs.

Aggregation Centers and Other Coordination. Comparing learning technologies ought to be a centralized effort supported by research infrastructure that limits the onerous organizational cost to individual projects. Establishing one or more real or virtual Centers for Collaborative Research on Learning Technologies would be an important step toward addressing such infrastructural needs in a flexible, effective, and efficient manner.[11] The purpose of the centers could be to undertake larger collaborative implementation/ research projects, to act as a technology transfer mechanism by training new researchers and by supporting prototype or model projects, and to act as evaluation centers for learning technology research. Understanding benchmarks or standards that can be used to compare work and finding ways to aggregate results and projects to build a larger understanding of learning are tasks well suited for a mission-oriented center.

Such centers would also be useful in solving another problem raised by workshop participants. The pipeline from research to publication and broad dissemination and adoption is a problem, particularly for small research groups and for individual researchers. Success may depend on infrastructural supports that are able to increase the ability of projects to:

- Develop the collaborations needed to work with school districts and with private-sector publishers

- Prepare teacher and student materials

- Ensure age-appropriate interfaces for children

- Improve software robustness, system maintenance, etc.

In a similar vein, the increasing complexity of products and services in the IT marketplace and the need for researchers to apply "systemically oriented" approaches calls for large-scale teaming. NIH and some private foundations have developed design networks that spend considerable time on coordinated standards, protocols, and intercoordination of activities, as opposed to the individual projects on which the participant researchers are involved.

Seed Grants. While large centers and centralized coordination are important for the learning sciences, NSF should not forget the innovative potential of small grant programs for exploratory and planning research. These small grants could leverage other research through "fire-hose talk" conferences, as was done successfully for the seed grants of a prior CRLT/LIS center (CILT, Center for Innovative Learning Technologies).[12] The meetings included five-minute talks by researchers, emphasizing research needs, as well as sessions for interactive demonstrations. In time, and with appropriate funding, we could foresee a phased model of seeding initial collaborations, funding the R&D period with traditional

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[11] The recently EHR-funded Center for Learning and Teaching "The Educational Accelerator: Technology-Enhanced Learning in Science (TELS)" is an example of one such center.
[12] http://cilt.org

funding, and providing follow-up support to sustain collaborations as projects seek other support for both staff and dissemination.

Other funding considerations. In addition, we offer the following suggestions, based on what workshop participants found useful in their own work:

- Fund mostly research projects that require collaborations involving researchers from more than one discipline. At a minimum, insist on a multidisciplinary advisory board.

- Encourage proposers (and reviewers) to think in terms of 5-year timelines and longitudinal studies. The full benefits of technology interventions may not be felt before 3 years.

- Projections for the evolution of the technology should be a routine aspect of funded projects, since maintenance and obsolescence will always cause problems.

- Although the research meeting had a definite emphasis on K-12 education in schools, much learning takes place outside the classroom. Interesting experiments in informal education and adult learning should be singled out as topics for proposals.

- Play, role playing, and games have been seen for a long time as important intellectual components of learning. This is still a little-researched area that promises high impact and leverage, given the multibillion-dollar market-oriented video game industry and its home penetration.

- Supplemental awards to projects such as EHR's Centers for Learning and Teaching, the STEM National Digital Library, the Science of Learning Centers, and Shared Cyber-infrastructure could foster a sustainable learning technology R&D infrastructure.

- There is interest in considering computational tools that give a time-dependent, longitudinal picture of student knowledge growth which leads to better assessment.

- Proposals should be sought to examine in depth some of the fundamental assumptions behind computer-based pedagogy—e.g., roles for digital video, simulations, visualization, and interactivity.

- Consider identifying examples or strands of work that point to what is needed but is not easily funded or that point to work that integrates what we know into larger constructs, e.g., dealing with interoperability; influencing teacher professional development; and conducting joint basic research in IT and social, behavioral and economic (SBE) areas, such as how IT needs to advance in order to better serve the learning needs of diverse audiences and cultures.

Promising Research Thrusts

I. Integrating technology and learning sciences

The talks in the research workshop described a number of very interesting and innovative applications of recent advances in IT that can greatly enhance the effectiveness and efficiency of teaching and learning practices. These included automated tutoring and self-learning environments, distributed information management and environments for sharing teaching content and for enabling collaborations among teachers, informal over-the-shoulder self-help environments, environments and techniques for automated student assessment to enhance efficiency, and others. Interesting issues discussed included the use of computations, simulations, and virtual worlds to stimulate learning; the creation of virtual laboratories; and the application of advances in the gaming industry to enhance the quality of instruction and effectiveness of learning. In this section, we describe promising research areas that came out of the research workshop.

Learning Environments and Tools

A promising research thrust identified by the research workshop is the integration of, and the interaction between, technological interventions and the surrounding curricular/instructional context, including the professional development issues that arise for teachers and schools adopting technology. The success of such projects appears to hinge on providing exemplary educational software that—at least in combination—cover a substantial portion of the curriculum. Such coverage is an important way of convincing teachers that technology can reliably support them on a daily basis. This would be a dramatic shift from the average 15 minutes per week of technology-supported curriculum, a statistic that dismayed workshop participants. Assembling software-intensive curricula will require cooperation among development groups and depends on significant design and software engineering research on both technological and pedagogical interoperability. (This issue of design and research was raised more broadly in the 1997 PCAST report mentioned earlier.)

Design-Based Research

In a related vein, there is growing interest in fundamental R&D issues around design-based research and in how we can use design methods to produce credible evidence of the effectiveness of design principles. There is also interest in reducing the time frame for iteratively optimizing the development processes. An in-depth discussion of this can be found, for example, in the volume edited by Kelly and Lesh[13] on research methodology. What is useful and credible design-based research and how "design experiments" can contribute to the field are questions that will be heard repeatedly in the near future.

Diffusing innovations and getting project success stories in the pipeline for large-scale implementation are tasks that call for qualitative methods, such as ethnographies and case studies, often discussed within design experiment methodologies. Research designs tend to pay too little attention to the marketing and deployment issues that will arise if

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[13] Kelly, A. and Lesh R. A., (2000). *Handbook of Research Design in Mathematics and Science Education*.

the work proves successful. Examples of such issues are arguments for designing flexible templates rather than full-fledged materials and software whose design remains hidden. If materials are too rigid, they become distorted when modified by their users—fidelity of implementation cannot be expected in view of the widely varying implementation environments in which they are expected to work.

Interoperability

Achieving interoperability of systems is important if we are to develop more elaborate and integrated interactive learning environments in less time. It seems fair to say that interoperability and reuse are currently the exception rather than the rule although some work has been done. Some general standards have been developed[14] however, their applicability for all the types of software designs that arise from learning science research remains to be seen.

Two groups represented at the training and implementation workshop have explored modularity within a context of interoperability. Ken Koedinger, Dan Suthers, and Ken Forbus' developed a prototype system that involved Koedinger's tutor, Suthers' collaborative argument diagramming tool, and Forbus' simulations. Roy Pea, Jeremy Roschelle, and Chris DiGiano explored modular educational software in their ESCOT work.[15] Both groups concluded that hooking up components developed in different places can be done. If the components share the same ontology, it can be easily done; otherwise, "translators" need to be built. Koedinger and DiGiano's point of view is that we should not expect to have many components with shared ontologies, and therefore, genuine "plug-and-play" compatibility will not be achieved over a wide range of components. However, building translators is a feasible approach if the components have been designed according to good software engineering practice. In the Koedinger, Suthers, and Forbus project, the integration of components was facilitated further since they had been designed from the start with an open client-server architecture and were therefore "scriptable" and "recordable." Participants remarked that the Open Agent Architecture was very useful in this regard.[16]

As course management systems gain in popularity in higher education and secondary schools, we should consider ways for them to effectively interoperate with research-based learning tools. The field needs to define the kinds of interactions that should be supported and either build new open-source course management systems/modules or convince vendors such as WebCT and Blackboard to accommodate appropriate "hooks." Open source would be preferable for supporting future research innovations; working with vendors may enable greater impact.

Infrastructure

An important issue is the development of authoring environments, tools, or techniques. We urgently need tools and software design methodologies that help reduce development time. Research proposals aimed at developing such tools and techniques are hard to fund, because they are not seen as advancing the state of the art for

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[14] http://ltsc.ieee.org
[15] http://www.escot.org
[16] http://www.ai.sri.com/~oaa/

information technology or providing new insights into what instructional systems work. A number of workshops devoted to authoring tools and interoperability have been held by the Artificial Intelligence (AI) & Education community. Also, in the past 5 years, two special issues of the International Journal of Artificial Intelligence in Education have been devoted to the topic. Progress has been made, but research aimed at developing more specific guidelines, practices, or principles for interconnecting separate components is still useful. Thought may need to be given to a possible long-term home for these projects if NSF's Experimental and Integrative Activities program is not appropriate.

With the experience gained from the development of the first generations of instructional technology, we are in a strong position to refine these technologies to achieve a better fit with classroom contexts and to make significant progress on the redesign of yearlong or term-long curricula and activity structures to take advantage of what technology has to offer. As several people pointed out, we are finally in a position, perhaps through partnerships, to design at the scale of the curriculum rather than that of a single software application. Doing so is expensive, and we still have much to learn about curriculum components. But the larger goal needs to be considered, and the technological infrastructure to reach it across projects needs to be explored and its requirements discussed among developers.

Assessment

Another promising research thrust is collecting, analyzing, and responding to assessment data. Classroom observations throughout a full term or year will increase our understanding of how teachers use and fail to use technology effectively. Ideally, these observations should be coupled with or added to multiyear observations of teacher growth in sophistication of use. Student assessment research that is sensitive to the learning goals of educational technology developers but that covers a curriculum rather than a technology-based unit would be important. All of this research should be comparative, both within and between projects. Within projects, research should be designed to get at the "value-added" of technology by comparing what teachers and students are able to do with and without technology and by understanding the conditions surrounding effective and reflective uses of technology tools and curricula. Between projects, research should focus on the educational outcomes of different approaches to integrating technology into the classroom.

To gather data relevant to their hypotheses, many projects use research-oriented assessment tools that may be impractical for everyday student assessment, including transcribed clinical interviews, videotape analyses, and essays coded by trained researchers using intensively developed rubrics. These research instruments must be validated against or converted into assessments that are practical in everyday educational settings, including embedding assessments in software and analysis tools able to deal with massive data sets. Technology, including lessons from data-mining research, can contribute significantly to our understanding of how to embed assessment in an efficient and effective way. We heard frequent mention of computer-based learning environments that generate volumes of keystroke-level data that in most cases are still waiting to be mined effectively. Collaboration with data-mining experts could provide a source of

fruitful new ideas and conjectures about assessing and modeling student learning. One application could be to provide insights into the conceptual growth patterns of individual students and the mapping of these insights into accountability testing.

Although not much discussed during the workshop, careful evaluation studies comparing the new methods with other methods—for example, more traditional methods of instruction and ways of learning—are particularly important. Coupled to these comparisons is understanding what kinds of evaluation results would be particularly compelling to educators, parents, or, more generally, society as a whole.

Simulations

Computer simulation is another promising research thrust identified by the research workshop. Simulations can help students learn how to explore problems, how to collaborate, and, more broadly, how to improve their learning strategies. However, they are most effective when they are under student control, as opposed to when they are used simply for classroom demonstrations. Janet Kolodner's description of what simulations are combines two ideas that could be considered separately: (a) working with a simulation rather than with the real thing and (b) exploring a phenomenon systematically (i.e., scientific inquiry learning). (It should be noted that simulations can be used for purposes other than learning through experimentation, e.g., simulations of complex equipment are very useful for training operators and maintenance staff and for practice prior to conducting laboratory experiments with fragile equipment.) Although scientific inquiry skills can be practiced and learned in contexts other than simulations, simulations under student control have much to offer when dealing with microscopic phenomena, microscopic interpretations of macroscopic, observable phenomena, and extremely slow (e.g., geologic) or extremely fast (e.g., electronic) events.

There has been little study of the design of interfaces for students and the general public that allow visualization and modeling to be effectively applied. Nor do we know enough about the kinds of knowledge that a teacher must possess to successfully use visualization and modeling environments as learning and teaching tools. Examples of particularly challenging simulation, visualization, and modeling contexts include complex STEM content currently not emphasized in curricula and the creation of learning environments that allow exploration of aspects of the real world together with their simulations (such as nanotechnology and current knowledge on the nature of matter in general).

In the AI & education literature, there is much work on the use of simulations for scientific inquiry (e.g., Smithtown and SMISLE). There is renewed interest in these topics, and in June 2002 a workshop on "Designing tools and methods to support inquiry learning" was held during the ITS conference.[17]

An important open question is how well students learn with simulations used for scientific inquiry, compared with other forms of instruction. In particular, compared with more "structured" forms of instruction, how well do they learn both in terms of domain-

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[17] http://www.itsconference.com

specific knowledge and in terms of inquiry skills (or, more broadly, self-regulatory skills)? Furthermore, we need to know when is best to use the simulation and when to do the real "hands-on" activities. Also, it is important to know more about individual differences between students learning with different levels of support.

Play, intellectual development, and learning

Another promising research thrust that emerged during the discussion is the role of play in human learning and the possibility that technology offers for creating play environments that lead to significant intellectual growth. Game theory and games as educational activities became somewhat confused at the research workshop. Game theory can be applied to any social system, whether or not the system is a game in the vernacular sense. One can use game theory to design learning environments that might or might not be presented to students as games. Using game theory to analyze and design learning environments is conceptually rigorous and generates testable predictions. Different issues arise when a learning activity is intentionally designed in such a way that students treat it as a game.

Games have been explored in the context of learning for a long time, but the discussion indicated aspects of the interaction that are still not clearly understood. From a practical point of view, new NSF programs should be concerned about the high costs of creating immersive, visually compelling, game environments that are on par with commercially available products. Given the level of funds absorbed in the creation of characters, story lines, storyboards, graphics, and the software infrastructure to support navigation and interaction, NSF should fund research into why these artifacts work and what aspects of role playing and game playing have educational value (beyond the obvious motivational qualities).

Play and human learning might be a candidate for one strand of a new program or for joint sponsorship of EHR and SBE. The field needs to go beyond the psychological assertion of the idea that students learn when they play and that this phenomenon can somehow be harnessed for academic development in an ad hoc way. More theoretical and empirical rigor should be brought to the area. NSF should consider encouraging collaborations involving psychologists and anthropologists with expertise in play. It would also be advisable to define play in a way that invites proposals for projects that use a range of models in addition to role-playing games. Research on smart toys is an obvious example.

Theory Testing

Learning environments that support higher-order learning goals. Research workshop participants agreed that a research area that continues to be ripe for exploration is the reform of traditional learning goals and the design of instructional methods to accompany "reformist" approaches. Reformist goals include learning to think like a scientist, learning collaborative problem solving, becoming a reflective learner, and acquiring 21st-century skills. It is premature to declare that we know that these things "work" and that we can simply get on with the straightforward business of implementing

them. They continue, deservedly, to be active areas of cognitive and educational research. NSF should continue to fund technology-oriented projects that explore these issues with a sound theoretical basis and research designs that accurately measure student learning.

Transactions between social and technical systems. A core concern of the research workshop was how to better understand the transactions between social and technical systems. The field needs to research the relationships between the online and offline behavior of students and teachers and understand how to organize technical structures in ways that support meaningful interactions. We need also to understand better how artifacts and technical structures can be used to promote deep collaboration, and there is not sufficient knowledge of how to promote social relationships through technical networks. The waters get murky when we are designing artifacts for complex systems and move beyond issues of usability to issues of sociability.

An additional issue in this sphere concerns how sociocultural contexts relate to the design and use of learning technologies. Such work may be pursued through ethnographic methods to better understand the contexts of use and the challenges of integrating successful technologies. There was also discussion about understanding technology in terms of the larger context. How should software be integrated into activity structures of the learning environment? How can software complement and stimulate real-world learning?

Cultural, group, and individual differences. The research workshop made it clear that there is still much work to be done on addressing cultural, group and individual differences in technology-driven research programs. Given the need for new ideas, it might be useful to simply invite applicants to address individual or group differences in their proposals. Projects that involve sustained, psychometrically informed investigations of the impact of technology on group and individual differences should be encouraged.

Compared to cultural and group distinctions, it could be argued that we have made the most progress with individual differences; for example, the CMU cognitive-skill tutors adjust to individual differences and have apparently been integrated into at least some classrooms in a way that does not disrupt the flow of classroom activities. Some of the projects that involve various forms of student-student interaction may involve productive approaches to individual differences. It is easy to design learning environments involving student interaction or collaboration that actually magnify student differences.

Two interrelated gender gaps seemed to surface often during our discussions. One is the well-known underrepresentation of girls and women in science and technology. The other is that girls and women might be disadvantaged by the increasing presence of technology in education. The question is whether we can design educational technology and the surrounding activity structures in such a way that they work for girls and women (and underrepresented minorities) and therefore generally help to address the disproportionately-sized pipes in the science and engineering labor pipeline. Using technology to support collaboration and to reduce the isolation and competitiveness of STEM education is a continuing area of promise.

An interesting aspect of the discussion of both gender and culture issues was the lack of theoretical depth, evidence, or a productive mode of discourse. Too many researchers rely on clichés, anecdotes, and secondhand knowledge in these areas. Although presumably a number of projects exist that purport to address group differences, it is reasonable to invite serious scholarly study of group differences in new proposals. Groups with technology in place in educational settings could also be encouraged to submit supplemental proposals that look at group differences within their projects. Sociologists, anthropologists, or social psychologists capable of framing the relevant issues and designing appropriate studies would have to be a key part of these projects. Collaboration with programs in NSF's SBE directorate should be sought. Group differences in educational technology would also be a suitable subject for another workshop like the two described in this document, which would articulate appropriate theoretical frameworks, the available knowledge base, and a research agenda.

At the heart of the "gap" issue is the lack of data as to how gender and cultural differences mediate students' interactions with technologies. The lack of in-depth conversations around gender and cultural differences is related to the lack of a conceptual model of how culture influences the design process.[18] Addressing these deficiencies requires the collaborative inquiry of a diverse group of researchers and the combination of new tools with existing methodologies, such as activity theory. Such special lenses are critical for exploring the interaction of culture on ways of knowing, seeing, and being. Often, the discussions around gender and cultural differences are not grounded in real data because of the lack of data-mining tools to facilitate designers' and researchers' reflection on students' interactions. Tools are needed to facilitate designers' and researchers' ability to visualize how users interact with technologies and to examine patterns of interactions across groups.[19]

What innovative styles of learning and teaching are made possible by the IT advances. There was some discussion on this topic, the key focus being peer learning. This includes different scenarios, from a group of students in a supervised collaboration to a more peer-to-peer environment where (potentially) anonymous peers engage in learning activities. Peer learning environments are a critical complement to teacher-student environments and could come to yield greater cost-effectiveness of learning environment design. For example, they provide a less intimidating environment for some students, and enable learning-by-doing and learning-by-teaching. Relevant IT research areas include multimodal (wire-wireless) collaboration, mobile agents, peer-to-peer collaboration environments, groupware, etc. For example, collaborative environments (possibly wireless and Web based) can provide a virtual laboratory where students can collaboratively work on an experiment or a design project. Furthermore, agents in the

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[18] Culture influences at least four aspects of the design of effective technologies: what we choose to design, how we design, how students interact with designed artifacts, and how researchers and designers evaluate the effectiveness of designed artifacts in achieving learning goals.
[19] Using such tools, one could assess how two variants of a proposed intervention, say Tanimoto's image processing tutorial, addressed group differences. In one variant, the technology directly incorporates features that address differences. In this case, the tutorial would provide collaborative problem-solving facilities and diagnostic agents for image processing. In the second variant, the technology is embedded in a learning environment that addresses differences independently of the specific features of the technology. In this case, the tutorial would be part of collaborative classroom activities.

system can be used to simulate "virtual peers" at different levels of learning that can steer the discussions in the group. For example, these virtual peers may bring out misconceptions by making obviously wrong statements and having students in the group correct them.

What future innovations in IT are needed to support innovations in teaching and learning There was very little explicit discussion about this topic at the workshop, despite its extreme importance. For example, there was some discussion about how much effort was needed to build certain capabilities with current technologies (scripts, sockets, etc.). This discussion indicates that these tools and technologies are not the right ones or don't have the right level of abstraction. New areas mentioned included wireless collaborative-access environments and peer-to-peer environments. Such instructional/learning environments lead to requirements in network quality of service, scalability, heterogeneity management, consistency management, multimodal collaboration, mechanisms for peer-to-peer accountability and reputation and trust management, etc., which are open research areas in IT and have to be explicitly addressed in this context. The field needs more discussion of the unique requirements and challenges of innovative paradigms in teaching and learning and how they can drive IT research.

Scale and Access

A crucial issue not yet fully understood is how to achieve solutions whose use scales well. We know how to make one classroom or school work, but what is needed is to have an ongoing, continuous impact in many schools. To develop tools and programs that scale well, the focus needs to be on a whole intervention (software, scaffolds, application, support) and on the learning activities that will take place with that intervention. Involvement of teachers and perhaps professional curriculum developers seems key, even if it takes a considerable investment of time to build up working partnerships. The typical NSF grant is too short to allow sufficient time to foster these partnerships and to work with schools and teachers in more than a one-time, experimental manner. Development of ways to make the materials and technology easily adoptable by teachers cannot be left to chance or to an added "dissemination phase."

Grain size is also an issue. Can we be successful only if we develop complete curricula? If not, what would be a "unit" of instruction/instructional technology that can be exchanged easily? Units that are smaller than complete curricula will be adopted more readily if they are designed to be integrated with widely used curricula, within a supportive, integrated environment.

Related to issues of scale, there was discussion about how technology transfer could take place and how technology could be disseminated and marketed (via publishers, spin-off companies, etc.). No clear success model has yet emerged. One success story mentioned involves Carnegie Learning, a company spun off from an NSF-funded research group at CMU. Other examples of NSF-funded work that became broadly used commercially include Geometer's Sketchpad and microcomputer-based laboratories (MBLs). At different times in the projects' long gestation, CISE, SBE, and EHR all contributed to the work that led to transfer.

Sufficient time for students to use technology is currently a bottleneck for getting instructional technology to "work" in K-12 education. (Technology access is a necessary but by no means sufficient condition for improving education through technology.) In Soloway's view, the basic hardware configuration that we can assume to be available to all students in all schools in the coming 6 years consists of one handheld device per student plus some Internet-connected computers in each classroom (considerably fewer than one per student). Indeed, reports indicate that public schools nationwide have closer to one computer for every five students, one Internet-connected computer for every seven students, and one "multimedia computer" for every nine students. (For details, see the publications listed at the "Technology Use in Education" web page from the National Center for Education Statistics[20] and the statistics shown on the Quality Education Data, Inc., web site.[21])

There was some disagreement about a proper balance in funding work with handheld and portable devices, laptops, and desktops. Each type has its own unique capabilities and features that are worth investigating. Desktops or laptops (portable machines with greater screen size than handhelds) will become cheap enough that they will be available for all students, if not 6 years from now, then soon thereafter. The mobility of handheld devices will provide complementary affordances, but we still need to understand all modes of access in terms of computing, networking, and display capabilities for learning technology interfaces.

II. IT: List of Strategies and key problems to address

- Focus on important problems and some of their metrics (e.g., fundamental gateways to the science and technology pipeline, such as middle school mathematics; core concepts, such as proportional reasoning, that are at the heart of much science; reading for learning to develop deeper understanding in the sciences).

- Establish "learning expeditions in networked systems" (LENS) that leverage President's Information technology Advisory Council (PITAC)[22] recommendations for developing Internet2, GRID, virtual instruments, and other advanced applications for learning and teaching.

- Make an effort to find convergence among information and communication technologies and emerging insights in the sciences of how people learn. Examples include the following:

  - Computer-to-student ratios for learners and teachers using ubiquitous mobile computing (handhelds and laptops).

  - Ongoing "take the pulse" assessment in learning anytime, anywhere.

  - GRID computing and students' model-based inquiry in the sciences and mathematics.

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[20] http://nces.ed.gov/pubsearch/getpubList.asp?L1=79&L2=0
[21] http://www.qeddata.com
[22] www.itrd.gov/pitac/meetings/2001/20010510/eisenberg.pdf

- Diverse technologies for customizing and personalizing information environments to fit learner interests and styles, information search histories, and learning histories.

- Just-in-time learning with repurposable learning objects.

- Integration of real-time classroom learning transactions using computers with back-office student information systems, a topic receiving industry attention.

- Digital video case studies, use of online learning communities, and other approaches to preservice and inservice teacher professional development.

- Personalized speech recognition for reading skill development.

- Design and study networked improvement communities that bring together multiple organizations concerned with similar improvement processes (e.g., interactive components for fostering middle school mathematics or science learning).

- Avoid assumptions of single-learner transfer of learning tasks, but consider instead augmented systems (teams, people-technology systems, integral use of tools).

- Identify emerging market trends that will bring into schools and homes new technologies whose cognitive or social consequences we do not fully know— online game environments, synchronous messaging systems and enhanced instant messaging technologies, and games on cell phones.

- Incorporate personalization and customization. How do we get to "task-ready" tools and online resources that are suited to an individual learner's needs in different domains or for performing different tasks?

- Identify appropriate economic models: copyright and ownership issues, thinking about the economics of scale, creating profit models for our innovations.

Discussions around these issues ultimately turned into deeper questions: How do we get practitioners and curriculum developers to value research efforts? How do we get policy-makers and publishing houses to understand the implications of our findings and incorporate these into their agendas? These are not research questions per se, but it is important if the education and technology research communities want to make an impact.

III. Education Research Strategies and key problems to address

- Understanding the importance of self-explanation is one of the most important learning contributions of the past decade. What are the different ways of helping learners do that? We need here to focus on what can be automated and what can be augmented, in terms of the activity structures to be supported (for example, tutors can automate, peers can help, scaffolding structures can help).

- Enhance the roles of peers in learning, through technology. We need to articulate what we know and understand about how to enhance these roles (for example, using over-the-shoulder learning).

- Use technology to promote better teacher learning. We do not have a clear conception of a toolkit for instructors separate from a toolkit for students and/or a toolkit for general work productivity.

- Recognize that assessment and learning supports (scaffolds) to the student are two sides of the same coin; how should pedagogy in use be informing the functionality of assessments in particular situations? How should what we know about learning inform the functionality of assessments? Helping people develop a "learning mind-set"—allowing them to make mistakes and explain them—might be quite important as part of assessment.

- Clarify cultural issues. Designers need to consider the many different cultural backgrounds and habits and styles of learners and how they influence individual and group learning. It is not as important to focus on gender and race per se as it is to find the characteristics of underlying cultures that make a difference (for example, "politeness" protocols, helping people interact across cultures and cultural expectations).

- Map the uses of technologies. Infrastructure is being built for the use of different technologies—virtual laboratories, simulation, modeling, visualization tools, and collaboration tools. What may be missing is understanding what kinds of student activities these technologies afford (e.g., how particular visualizations promote understanding) and how to integrate them with each other (i.e., which ones when and in what combinations). Languages that allow learning technologists to describe the affordances of different representations in the teaching and learning of concepts would be extremely helpful.

- Improve our understanding of how to use virtual laboratories. In what ways does access to complex equipment make a difference? What are the pros and cons of getting to run the equipment at a distance versus running a simulation? How should virtual laboratories be integrated with simulations?

Learning Technology Training and Implementation

To orient the discussion, and on the basis of participants' interest and expertise, the training and implementation discussion focused on three aspects of learning technology:

- Engineering: Design engineering issues in learning technologies. What are best practices for consistently creating effective learning technologies? How can this creation be done efficiently? What aspects of high-quality educational technology are difficult to capture as engineering principles?

- Training: Preparing professionals for design and development of learning technology. How can we best prepare researchers and developers who will need to work simultaneously with educators and technologists? How can we communicate key concepts (e.g., how people learn, the roles of the teacher) to the next generation of education technology developers? Are there best practices for education technology training (e.g., curriculum design, project topics, infrastructure)?

- Implementation and Impact: Putting the lessons to work. How do researchers identify the best roles for technology in a curriculum? How does the field work with education stakeholders to ensure adoption? What are the barriers to implementing educational technologies so they can have the impact they promise?

Design Engineering Issues in Learning Technologies

The software infrastructure we are trying to build is still either too brittle or too inflexible.

***Differences between designing learning technologies and designing other systems**.* Participants highlighted the significant difference between designing learning technologies and designing other kinds of technologies. First, participants argued that student learning is a special kind of outcome that needs to be treated differently from other kinds of software or human performance goals. Learning outcomes are harder to test in one's software. Often, understanding or knowledge transfer does not manifest itself immediately. This is in contrast to testing whether users can make use of a new feature. Second, it is often the case with learning technologies that teachers themselves will be adapting the content. This middle person, although critical in the learning technology context, complicates the delivery of the software. Third, developers of K-12 educational software currently must target a large variety of platforms and configurations to reach a large audience. Old donated PCs further complicate this situation. Fourth, resources are scarce for developing and testing learning technologies. It is difficult for teachers to find the time to invest in learning new technologies. Finally, there are social barriers, which make it difficult for developers to really understand the needs of their users and for users to be able to articulate what they need.

We should point out that researchers are beginning to call for learner-centered design to be used more often in more general user-centered design problems (see, for example, the work of Soloway, Guzdial, and Hall[23]).

Lack of commonality in approach. Participants expressed concern with how limited research resources are being spread across a wide variety of technical strategies for learning technology. First, researchers are implementing their own tools with a wide variety of programming languages, from Java to Smalltalk, Python, Lisp, and C++. This lack of uniformity limits the ability of the relatively small learning technology development community to leverage each other's advances. Libraries supporting various types of functionality for educational software have emerged for each of the above languages. However, this work is still too fragmented to enable the kind of reuse that is needed to make the engineering of learning technologies efficient.

Another way that engineering resources are being spread thin is in targeting a wide variety of classes of users. Target audiences mentioned by participants included students, teachers, curriculum developers, and other software developers. Each of these classes of users obviously needs a very different type of software. Students need systems designed around learning outcomes, typically with the classroom environment in mind (e.g., the system gets used in 40-minute intervals). Teachers need systems that can increase their productivity or help them assess student learning. Curriculum developers need systems that help organize content, drawing from libraries of media and standard references. Software developers need systems to help them build still other systems for the various target audiences. This last category is an example of a meta-audience—that is, a class of users who themselves need to create derivative learning technology products. Meta-audiences further fragment learning technology engineering work.

Lack of common specification languages. Participants expressed concern over the lack of standard techniques for appropriately specifying learning technology designs. Without common systematic techniques for capturing the high-level and low-level functionality of educational software, participants worried that critical aspects of the system design will continue to be overlooked, with new generations of designers repeating the mistakes of previous generations. Without proper specifications, researchers tend to build systems based on potentially faulty intuitions and assumptions and only discover their mistakes through expensive testing. One participant described this strategy as "ready, fire, aim."

At the same time that participants raised concerns, they acknowledged the difficulty of converging on a common formal language for specifying learning technology designs, given the variability of target audiences and the endless types of instructional strategies. Indeed, a badly designed common specification technique runs the risk of overly constraining designs and limiting creativity.

Participants reflected on the kinds of specification tools, such as Unified Modeling Language (UML), used in general software engineering. An open question was why we cannot adopt such professional tools in learning technology. Education-specific tools do

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[23] Soloway, E., Guzdial, M., & Hay, K. E. (1994). Learner-centered design: The challenge for HCI in the 21st century. *Interactions, 1*(2). 36-48.

exist, such as Educational Modeling Language (EML), and metadata efforts for describing finished products (e.g., SCORM, etc.) could be harnessed at the design stage. We need to understand what is needed to make these more widely used and to evolve with learning technology engineering practice.

Recommendation: *Encourage quality control initiatives.* One can claim that the problem with learning technology design is not that there are too few tools, but that the standard of quality is too low. To address this concern, participants had two recommendations:

1. That new initiatives be launched to improve the reward structure for high-quality products.

2. That the learning technology distribution network be improved, so that the high-quality technologies reach their intended audiences.

The rationale behind the first recommendation is that, too often, learning technologies are being created in isolation by intuition without validation by the larger learning technology community. New structures are needed to ensure that systems are properly vetted and that high-quality designs receive public recognition. One specific idea for a reward system is to organize competitions for professional learning technology efforts, as well as amateur efforts by, say, having university students create learning technologies as part of a design project.

But recognizing the best efforts is not sufficient. Exemplary works need to be promoted by making it easy for teachers and students to find the high-quality content. We need to avoid diluting digital libraries with so much educational software that it becomes difficult for teachers to make good choices about what tools to use in their classrooms. Content needs to be properly cataloged and labeled to simplify the process of appropriating tools. Participants suggested that platforms for installing and trying out software could also be improved. They pointed to SqueakMap[24] as an example of how simple it ought to be for users to find software of interest and run it.

Recommendation: *Encourage cumulativity of knowledge and artifacts of learning technology design.* The design of learning technologies needs to transition from art to science. Although this work inherently deals with ill-structured design problems, there is such a thing as a science of design. To approach work more scientifically, participants encouraged efforts at formalizing design knowledge and capturing exemplary works in reusable form. Participants recommended more meetings like this workshop, which brought together learning technology designers to share their techniques and reflect on the invariant principles behind the most successful approaches. Repositories are needed to collect these lessons learned. Candidate design principles that were discussed— admittedly at a very high level—included:

1. Scaffold/encourage/enforce best practices; study what is already working well without technology.

2. As a cognitive principle, minimize the needed working memory of learners.

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[24] http://map1.squeakfoundation.org/sm

3. Build on learners' prior knowledge.

4. Consider domain-specific designs for different learning settings/needs, including alternative platforms such as PDAs, cell phones, and game machines.

5. Make software easy for teachers to use and understand; they are the gatekeepers.

6. Consider targeting teachers instead of students as users; help them be more productive and effective in the classroom.

7. Allow for scripting languages, so products can be customized.

Participants also recommended that we work harder to build on best practices in related fields such as software engineering, human-computer interaction, sociology, cognitive psychology, anthropology, machine learning, data mining, and natural language understanding. For example, learning technology developers should make better use of automated regression testing from software engineering to improve the robustness of their code; HCI offers techniques for evaluating software; and data-mining techniques can be used to analyze log files. The challenge for learning technology designers is finding the relevant techniques and appropriating or adapting them for our field.

Recommendation: *Explore "discount" techniques for design of learning technologies.* The field of usability engineering has evolved a set of heuristics for arriving at effective interface designs quickly and with a limited budget. For example, Jakob Nielsen has long been promoting what he calls "discount" usability techniques. Similarly, the field of learning technology design needs a careful cost-benefit analysis of available techniques to arrive at a prioritized set of approaches that have the most power for the least effort. Obvious points of leverage include the reuse of robust, off-the-shelf components and libraries, the use of open-source code that can readily be learned from and patched, and the adoption of well-thought-out standards. Areas that need new learning-technology-specific standards include assessment, knowledge representation of subject matter, ontologies of subject areas, and student modeling.

The last two categories of recommendations, encouraging cumulativity and exploring discount techniques, depend on an improved understanding of the practice of learning technology design. *For this reason, a major recommendation is that more resources be devoted to a microanalysis of "what works."* The current "What Works" initiative tends to be at the macro level, with whole interventions labeled as either working or not. Engineers and designers of learning technologies need lower-level data (one participant went so far as to suggest that we analyze individual lines of code) that help them predict what types of system features will lead to what kinds of learning outcomes.

Preparing Professionals for Design and Development of Learning Technologies

Designers and developers need specialized training, but the specific needs have yet to be organized into a coherent and agreed-upon curriculum.

Emerging powerful course models. There was general agreement at the workshop that at universities in the United States and in other countries, some particularly powerful course models are emerging for training a new generation of learning technology designers and

developers. Most courses emphasize a team-oriented, project-based approach in which students work together to solve different aspects of a small number of ill-structured design problems.

Course models vary in the source of the design problems. The instructors fabricate some problems, while other problems come from real-world clients seeking learning technologies. These clients come from the local community, from commercial sponsors, or from university faculty. When clients are involved, especially noncommercial clients, these courses are usually framed as "service-learning," since students are effectively volunteering their time.

Project-based service-learning experiences do not necessarily limit themselves to applications of learning technologies. In fact, such applications tend to be just one of many project options for students in a course. Such a wide variety of project types can make the choice of readings, lecture topics, and assignments difficult.

Participants have learned to value training experiences that involve both technical and pedagogical perspectives. Several models are being practiced. In one, students are studying primarily a technical discipline, such as computer science, and they consult with those with pedagogical expertise, such as practicing teachers. In another model, students work in multidisciplinary teams representing both technical and pedagogical perspectives. The latter can come from education students (the course can be cross-listed as a methods course) or experienced teachers on releasetime. Yet another approach is for the education perspective to come from a lab instructor, such as a master's student in education.

Benefits and risks of specialized training in learning technology design. Participants agreed that building nontrivial software was an important experience for technology students. However, participants also described challenges in maintaining student-built software, once delivered to clients. Instructors and students must be careful to avoid misrepresenting the robustness of their products and the kind of support that clients can expect. *In participants' experience, the quality of student products can be increased by extending the course to cover more than one quarter or semester.*

It should be noted that there was no clear consensus on how educators or educators in training can benefit by participating on or interacting with design teams. Potential benefits from being involved in design decisions include:

1. Increased awareness of the potential applications of technology in the learning environment.

2. Increased confidence in critiquing learning technologies.

3. Networking opportunities for connecting with technologists who could help design or customize solutions for future needs.

However, there was debate about whether educators should be trying to actually build educational products. Some argued that most teachers want to learn to make editing-level changes to learning technologies, but not to create new content. One participant suggested that a better model might be to involve students, not teachers, in authoring

learning tools. Participants saw the combining of technical and pedagogical perspectives—through multidisciplinary classes or other models—as particularly beneficial. Advantages include:

1. Requiring multiple perspectives demonstrates to students that learning technology design is complex work that is not circumscribed by any one discipline.

2. Students learn to work in a multifaceted team environment that gives them realistic experience for professional design work.

3. The act of communicating and negotiating across disciplines can help participants from one perspective gain a new appreciation of the other perspective. This appreciation can be helpful later when working in less-than-ideal conditions, when participants may need to make decisions without representation from the other discipline.

Participants have learned some important lessons about the challenges of specialized training in learning technology design. A recurring theme was the challenge of getting technology students interested in designing learning technologies as opposed to business, scientific, or gaming applications. The lack of recognition and the limited financial rewards in the field, especially as compared to these other opportunities, is a problem. As a way to get technical students interested in pedagogical issues, one participant first assigns such students to study the extensive literature on teaching programming.

Participants also discussed how getting students from multiple disciplines to appreciate each other's perspectives can be rather involved and take valuable time away from other activities, such as writing code or conducting field trials. This problem is particularly exacerbated by the overconfidence that many had observed, particularly in technology students. In addition to all the other kinds of training these students need, they must learn how to approach the task of learner-centered design with humility and patience, recognizing that in some cases technology may not be the answer at all.

Key concepts in training new designers and developers of learning technologies. In the workshop, participants compared and contrasted the concepts that had emerged as fundamental in training new designers and developers of learning technologies. In the recommendation section, we are more speculative and expand on this list to propose the outline of a complete curriculum. Here we list some of the key concepts that were grounded in training experiences:

1. Practitioners need to rely on user testing rather than intuition to guide their designs. Too often, design intuitions are misguided, especially those of novices (see above comments on the problem of student overconfidence). Students need to learn to justify design decisions on the basis of feedback from representative users or data from the ethnographic, cognitive, or pedagogical research literature.

2. Trainees need to keep their designs simple, or else they will not get beyond basic usability issues to wrestle with the more interesting pedagogical problems.

3. Students have different learning styles; what style an individual applies can be context dependent. Learning technologies need to be flexible in their pedagogy and, ideally, adapt themselves to a given user and context.

Recommendation: *Promote an Educational Technology degree program.* A major recommendation from the workshop was that specific Educational Technology degrees be established and standardized across the country. This was envisioned as a master's or PhD program that emphasizes learning, psychology, curriculum design, and technology development. Suggested topics for this degree program are:

1. *Evaluation and Assessment.* How to determine the impact of learning technologies.

2. *Motivation.* How to learn from the success of gaming, etc.

3. *Design.* Processes for envisioning and building new or derivative learning technologies.

4. *Perspectives on Educational Technology.* Who the stakeholders in learning technologies are (e.g., educators, instructional designers); how to work with them effectively.

5. *Working in Schools.* The mechanics of arranging and executing classroom observation and testing.

NSF should consider funding groups to organize these ideas into a coherent degree program that has buy-in from major institutions. Furthermore, funding is needed to encourage broad participation from students in technical and pedagogical disciplines, including sociocultural studies. This could involve funding enticing design competitions or providing monies for granting release time to practicing educators.

Recommendation: *Collect best practices for training that can inform new degree programs.* Many workshop participants are already involved in training a new generation of learning technology designers, and we are aware of many other efforts. These can be seen as progenitors to a standard Educational Technology degree. Georgia Institute of Technology, for example, offers courses titled "Introduction to Educational Technology," "Design and Analysis of Educational Software," and "Computer-Supported Collaborative Learning." We recommend collecting the best practices from these and other efforts and making them available to the entire community, especially new instructors.

A project called "Training and Resources for Assembling Interactive Learning Systems" (TRAILS)[25] is starting to organize best instructional practices around the topic of design of learning technologies, and will be publishing them to pilot course sites around the country. Other projects are needed to capture best practices in other subfields, such as evaluation, assessment, and motivation.

Recommendation: *Use learning technology to teach learning technology.* Participants recommended that the training of specialists in learning technology be seen as a learning technology design challenge itself. Further research is needed to identify the best ways that technology could enhance the training experience. A promising direction would be

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[25] http://www.trails-project.org

to explore inquiry environments that could provide intense training experiences in a short amount of time. For example, such an environment could expose trainees to the rigors and surprises of classroom testing of learning technologies without the need for trainees to arrange for actual testing in a nearby school. Videos could show exemplary testing stories that trainees may be asked to study and discuss.

Putting the Lessons to Work: Implementation in and out of the Classroom

Preparing developers of learning technologies must include attention to performance in and out of the classroom as the measure of success.

The discussions on effective implementation of educational technologies benefited appropriately from the topics and ideas about both software engineering and educational technology discussions. The implementation lessons and recommendations thus have some overlap with what has been presented before. The following discussion nevertheless provides a different perspective and rationale for common ideas that will be revisited in the Conclusion section.

The Importance of Mixed Expertise: Forming design teams with expertise in both technology and learning. Research represented by workshop participants has identified the importance of design in the development of learning technologies (see, for example, the CILT Design Principles Database and the workcircles of the LeTUS Center). Until teachers understand the design behind a technology, their use and adaptation of the technology would most likely work against crucial design features. The workshop participants noted that there are design principles for implementation that technology designers need to know and adapt. As examples, only if the software meets a real need for teachers or parents will appropriate attention be paid to its use. Needs assessment could be a time-saving activity that will improve technology development and lead to demonstrable learning outcomes. The tools should be adaptable, anticipate teacher modification, and be usable across multiple designs. Other principles with direct relevance to implementation will be discussed under the other lessons below.

An important experience for technology developers is to engage in needs assessment with teachers before choosing a problem or selecting a design approach. There is often a mismatch between stated needs and technology capabilities; there is no simple answer, and a useful negotiation requires cycles of interaction and revision. Design should be driven by demand and avoid offering solutions to nonproblems. Good practices are:

1. Asking teachers and faculty specialists what they have trouble teaching.

2. Asking teachers and faculty specialists what students have trouble learning.

3. Asking teachers what they themselves would like to learn.

Negotiation can be a lengthy process; teachers know the problem but rarely know the solution, and it will be up to the technology developer to formulate possibilities, for which he or she will need to look at learning sciences research.

Solutions to real problems often need to be conceptualized from several points of view— for example, use by teachers, learning needs of students and their assessment, integration

with classroom activities. This consideration by itself indicates that a design team of several learning technology developers, teachers, education experts, and even a student or two may lead to both deeper learning by the developers and a more usable product, and eventually to better uses in practice.

Depth of Understanding: Students' understanding learning science concepts in some depth. If there is a lesson that seems hard to learn, it is that only so much intelligence can be incorporated into the software. How software is interpreted and how it gets used are of paramount importance, and the ways are as varied as the number of teachers who will use it. Developers often look for solutions in the technology itself, when learning technology researchers have found that it is better to think in terms of inevitable changes (i.e., make the technology flexible and adaptable) than to expect a high level of fidelity to envisioned practices during use. Teachers must take as much advantage as they can of the "teachable moments" when and however they occur in their practice. Learning happens between instructor and student, and it is impossible to predict all the forms that such an interaction can take. Design that incorporates an understanding of the range of associated educational practices will lead to products that will be used more often than those from a highly constrained design.

Besides the obvious challenges and time constraints imposed by access to appropriate technology, there are other barriers to development posed by the different professional languages used by educators and by developers and by the accountability for their students' learning that teachers must keep in mind. It often falls to the developer to surmount the barriers, at least initially, since time pressures on teachers are a constant reality in education, particularly at the precollege and community college levels.

As part of their professional growth, developers should be aware of what resources they can bring to the table *in addition* to their technology knowledge. Identifying such knowledge requires attention to learning sciences and learning sciences research. In particular, there is a strong cognitive technology research strand in the learning sciences that should be part of the professional knowledge base of developers. for example, the conditions for and advantages of conducting time and motion studies of teachers (workflow efficiency), identifying inappropriate uses of technology in the curriculum, and suggesting existing ways to solve a given problem.

An important learning technology design principle for implementation is that the integration between technology and other classroom practices will dictate the usefulness of the technology, and therefore its adoption. Work should be grounded in a research base and in knowledge of successful practices. Informal conversations and other low-cost ways of helping developers understand how teachers look at learning are not sufficient to achieve success. How to listen to "the client" must be part of the toolkit of every well-prepared learning technology developer.

One other crucial aspect of that preparation is to look at measures of learning performance. Pedagogically, teachers want to have data available for each student. Obtaining performance data is critical, and developers would help their cause by being able to record such data for teachers and provide tools for teachers to analyze the data.

Many analysis tools are available that can be integrated into whatever product the developer is considering.

Revisiting software: designing for maintenance and support. The two prior implementation lessons lead directly to a third one: not all learning technology development should be based on a new idea. Replication of existing work and a study of its adaptation to new environments can lead to sophisticated ways of understanding how to generalize between classrooms and of separating local idiosyncrasies from fundamental practices.

In fact, innovation and implementation interact in many different ways. Innovation that starts from scratch is simultaneously a high-risk and high-gain proposition, and may deal with pedagogy and with sequencing of content topics, and so on. Innovation may lead to cases where laboratory studies may provide the knowledge to proceed to an implementation stage. Innovation on classroom implementation requires working directly with schools in a research mode, recognizing that classrooms are complex, integrated systems, and attention must be paid to design issues that will help with generalization to different environments. CILT's Synergy project[26], for example, looked at the implementation of similar content and tools in four quite disparate classrooms, in an efficient interaction of research, implementation, replication, and classroom support, to bypass the "isolation culture" of each school and ultimately to obviate the need to solve the same problem for each individual classroom.

The process of replication brings an added advantage, as found by the U.S. Department of Education Expert Panel on Educational Technology.[27] They found that preparing a description of one's program for communicating it to others in specific detail *so that it can be applied and modified in a different context* will uncover crucial steps, allow exploration of optional ones, and point to other paths to optimization. Addressing replications implies attention to and documentation of usage contexts, beyond the obvious one of technology availability. Of importance are the effort, real and perceived, of implementation; equity considerations; adoption issues; resources available in urban, suburban, and rural environments; different assessment and performance measures; and many other characteristics that define the practice of local education systems. Attention to these issues strengthens the robustness and focus of a design and software product.

Recommendation: *Support research on implementation explicitly in calls for education proposals.* The creative interaction between the development of learning technologies and the strategies for their implementation parallels the interplay between theory and experiment in other research situations. Too little emphasis is placed on reflectively adapting experiments that are successful as isolated islands of innovation. Even less priority is given to modeling and generalizing the coherent processes that led to these experiments. Developing the skills and methodologies for such work should be an integral part of any program on learning technologies. This issue can be considered one of capacity building and of creating the *human infrastructure* needed for future applications work.

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[26] http://cilt.berkeley.edu/synergy
[27] http://www.ed.gov/pubs/edtechprograms/index.html

In fast-moving environments like the present, research offers baseline information more often than guidelines for effective future action. The balance between "general," "generalizable," and "localized" knowledge acquired from research is usually not clear or even present in research portfolios, and this ambiguity contributes to the problems and barriers described in the training and implementation sections of this report

In most cases, it takes a long time, on the order of 5 to 10 years, to establish effective collaborations between researchers and school systems, and during this period there may be a need to renegotiate and recommit to goals and strategies developed together whenever there are major changes in leadership or personnel on either side of the partnership. Implementation research requires longer-term funding. The fruits of reform efforts tend to become visible only after 3 to 5 years, so that evaluations and tests of scalability require at least a second or third cycle of enlargement or replication, as many new NSF programs (including IERI) have recognized.

An education research group at George Mason University that addresses the meaning of "dissemination of educational innovations"[28] highlighted the overlap between "dissemination" and "implementation research." This group defines dissemination as "*the successful adaptation of an innovation in a new environment*." Among the important insights of the group is that all educational innovations are in fact embedded sets of strategic requirements; a learning technology innovation must be supported by teacher's appropriate use of the innovation, which requires teacher professional development of a certain type, as well as new methods of assessing learning. Models and benchmarks of progress must support the strategic process. But very little is known about this process, whose growing practical importance is an outcome of the increased educational use of ever more advanced and flexible technologies.

Dissemination and diffusion of classroom innovations are a "people induction" process, and thus require that additional thinking and time be made available before it can happen. Dissemination and adoption processes also need access to a stable support infrastructure oriented to the uses of technology in learning, to allow teachers and developers to focus on central issues of educational use, rather than on peripheral issues of software usability and robustness, network stability, or intermittent access.

Implementation research will provide the knowledge base on which an infrastructure able to support the reform of educational practices can flourish.

Recommendation: *Support the development of informal curricula and online courses for designers of learning technology*. There is not as yet a clear definition of the knowledge base needed to develop a broad base of researchers and developers capable of studying and serving the needs of large-scale technological educational innovations when implemented in complex environments, and at many different points in the continuum of basic to applied (including systemic) research. An informal consensus about the conceptual—not only disciplinary— components of such a knowledge base will begin to address some of the communication barriers that constrain advances in integrating the work of technology and learning practitioners with the potential applications of the work.

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[28] http://gse.gmu.edu/research/de/

In the absence of such understanding, the path of least resistance is to limit prerequisite knowledge to technology and give short shrift to principled design and to the lessons from research; this is as true in university courses as it is in private-sector software development. Developing effective and integrated curricula is further constrained by the paucity of developers knowledgeable in both learning sciences and technology. Offering professional and for-credit online courses, for specific target audiences, could catalyze the growth of a larger community of expertise.

The advantages of understanding the conceptual bases of the field are addressed in both the training and implementation sections of this report. One way of addressing these needs, and of developing a better understanding of the role that learning sciences research can play in advances in the field would be to sponsor a series of research summaries based on theories that present validated current research results to a larger audience of developers and policy-makers. These presentations could provide useful answers, provide analyses of results generalizable to other real-world educational situations, and develop insights for wide discussion.

Recommendation: *Consider ways of building the infrastructure that is integral to scaling learning technology use*. Demonstrating the benefits (if any) of research on practice requires that successful outcomes be scalable to larger systems, work for different student populations, and be sustained over longer periods of time. In fact, it requires a process of "continuous improvement" rather than a one-time-only quality jump. Thus, research attention has to be paid to scaling up and replicating successes in complex situations and to sustaining these improvements in practice over time. Without the integration of an experimental research mind-set in all aspects of the education system, the impact of cognitive, pedagogical, and technological innovations on the practice of education will remain limited.

It is very hard, if not impossible, to build infrastructure piece by piece and project by project. Both human and technological support infrastructures are crucial to the ultimate success of learning technology in transforming education practice in response to workforce needs. *What the training of future learning technologists can accomplish is underpinned by the infrastructure that is available for their practice work*. Fostering the potential capability of emerging information technologies to enhance learning and teaching; to improve the organizational efficiency and effectiveness of schools; to enable partnerships for learning among teachers, parents, employers, and communities; and to develop new tools and methods that empower the process of knowledge generation and communication requires the presence of a stable infrastructure for the education system as a whole. For example, the usefulness of cell phones is directly proportional to the number of users that they can reach and presupposes the existence of a national network that interconnects regions and providers.

Research on a cyberinfrastructure for education should provide models of smaller- and larger-scale units of analysis (individuals, classes, schools, districts, city systems, state systems, etc.) and processes on short and longer time scales of change (lessons, daily schedules, courses, cumulative student learning, teacher professional development, curriculum changes, management changes, policy changes, changes in social attitudes,

etc.). In particular, the workshop participants were interested in seeing education specifically addressed by the NSF middleware initiatives. In the same way that learning technology applications have fundamental differences from other technology applications, the infrastructure needs of education need to be addressed directly if progress is to take place at a reasonable pace.

Classroom education is localized, and schools are isolated from technology and workplace changes. Creating school or district "testbeds for innovation"—perhaps better named "pedagogical laboratories"—that help schools explore what can be achieved in their own environments would provide a common training ground for developers and teachers. Testbeds should not be demonstrations or existence proofs; rather, the should be working laboratories serving districts, teachers, and students.

Schools will not innovate without assurances of either succeeding or documenting that they "did the right thing"—every cohort of students must succeed. Researchers are needed to make flexibility and experimentation safer for teachers, who must respond to fixed local accountability and curriculum standards. Developing a *multiyear* "partnership" that can adapt or develop the technologies *needed locally* and can interact with teachers to support best practices would be an efficient use of resources.

Overarching and Cross-Theme Issues

Putting together what we know—enabling schools to change is not the same as studying them, or creating materials for them, or helping them do only slightly better what they already do, or doing something sporadically or at the margins. It is empowering them to move from where they are to where we all want them to be—and where a democratic society needs them.

Ready and reliable access to powerful, networked technologies, and the presence of a support system to allow citizens to take advantage of them are at the heart of a sustainable, high-quality future for all. Education is the testbed where all citizens will learn civic and responsible uses of information technologies. There is ample evidence that new tools to empower broad-based learning must be crafted in collaboration among diverse stakeholder professions. No group alone can make the necessary progress; all have needed expertise to contribute, and all learners must be ultimately ready to contribute to this future.

Rather than point to an impending crisis and issue calls to action that are often little more than exhortations to be good, more may be accomplished by concerted action to scale up and integrate knowledge and expertise concerning conditions for success. A number of national programs—notably IERI, PT3, and TPC—have invested significant resources in implementing applications of technology to education, and work is needed to extract usable lessons from them in the form of principles or best practices.

Such programs are experimental, but they have the potential to result in more than the sum of their parts. Currently, they are fragmented and unassembled—both within and across stakeholder communities—because there is little awareness and cumulativity, there are few common protocols and standards, and priority-setting exercises are not the responsibility of each individual program. For these programs to reach their potential, a common infrastructure is needed to provide strategic direction so that each program can have some flexibility, but across programs there is still coherence. The development of basic technologies that are in use in education has been conducted, until now, in collaboration only with research needs and experiences in mind. It is time that the experience and environment of education (the needs of 40 million precollege students, for example) directly inform the development of learning technologies.

Internet2 convened a group to look at issues of the Abilene Network for K-20 education. Though the ongoing work of Internet2 followed a different path, the diverse group of researchers, technologists, and policy-makers that gathered developed a vision of what an education-oriented infrastructure should support and of how to gather the knowledge required for it. A version of this vision can be found in the report of an NRC workshop.[29]

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[29] Pea, R., and Lazowska, E. (2003) "A Vision for LENS Centers: Learning Expeditions in Networked Systems for 21st Century Learning." In Pea, R., Wulf, W.A., Elliot, S.W., and Darling, M.A. (Eds.). *Planning for Two Transformations in Education and Learning Technology: Report of a Workshop*. National Research Council.

The vision highlights the need for:

1. Bootstrapping: evolving guidelines for the formation of high-priority projects.

2. Thought leadership in garnering funding and support for such projects.

3. Harvesting and sharing best practices in a persistent portal-like knowledge network.

4. Providing project home-base support to enhance cumulativeness.

Particular projects might, for example:

- Define and develop scalable protocols and policies for educational uses of public databases and other public resources (including scientific instrumentation).

- Reconceptualize educational practices and curricula on the basis of dynamic representations made possible by new technologies.

- Investigate the capabilities of advanced networking to access tools not currently used by the K-20 community.

- Create/coordinate a cohesive infrastructure for the use of broadcast and interactive video for education.

- Accelerate the emergence of an integrated advanced Internet infrastructure focused on educational institutions at all levels nationwide.

More directly relevant to this report are the following:

- Develop network-based tools, frameworks, and communities of practice to facilitate ongoing professional development for technologists, educators, and administrators.

- Develop network-technology-enabled assessments to guide instruction in realtime and evaluate these according to national and state standards.

- Engage policy-makers, college boards, and administrators in the process of defining applications so that there is a deeper level of knowledge of how to better use networked-based applications in a sustainable manner.

Final Words

It should be clear to readers of this report that the meetings were productive. The discussions, though wide ranging, could not cover all the topics in the interface between information technology and learning sciences that are of interest to both communities. There was a significant presence of researchers who have been working at this interface and of others who see the need to do so. Workshops of this type make their most important mark in forging personal links among researchers, but the insights that come from such a meeting should be available to all interested researchers. We offer these notes with the hope that others may find them useful.

The broader research reflected in these ITR workshops is not of uniformly high quality, in either technology or learning science. In this way the knowledge base represents the field was representative of the field. This report reflects the discussions, since many other researchers will find themselves in similar positions. Some of the suggestions made here will undoubtedly be seriously discussed during the peer-review process of NSF programs, which is a better filter than the few individuals whose thinking is integrated here.

In view of the importance of building up the research capacity at the interface of research and practice in education, we suggest that NSF consider the following strategies, in addition to the call for research proposals:

1. Invite a series of proposals for workshops to explore the potential of some of the interesting ideas, including some put forward in this report.

2. Fund a number of conceptual literature reviews designed to bridge the gap between the professional journals read by both communities.

3. Establish three or four centers that, together or separately, have three main purposes:

   - Help other projects understand educational needs, requirements, processes, etc., and facilitate the required collaborations

   - Help projects understand education research and technology evaluation

   - Serve as coordinators and aggregators of resources, technologies, etc.

4. Set aside funds for a significant (e.g., 10) number of planning grants at the $250K level, and encourage interested research grant applicants to participate in the workshop and center projects.

It has become clear to many in education that research in education technologies has taken on aspects of rethinking education practice in more general terms, since technology is seen as an entry point for innovation. There are good reasons for this development, some of which hark back to the effective role that NSF has played in funding many of the innovative ideas and tools whose impacts we saw reflected in the workshops.

Technology is a tool that has proven transformative in other application areas. Education as a whole has not yet followed suit. The interest that education practitioners and policy-makers have expressed in understanding technology use suggests that transformative uses will be given serious attention. For this to happen, a balance needs to be achieved between innovation per se and the discipline to research significant issues of practice—what has been known lately as "Pasteur's quadrant" work, or use-driven research. The types of projects and centers that NSF funds in the future should continue the tradition of coupling system research and development with shedding new light on practices so that the resulting whole is more than the sum of the parts.