

Fostering Learning in the Networked World:

The Cyberlearning Opportunity and Challenge

A 21st Century Agenda for the
National Science Foundation

Report of the
NSF Task Force
on Cyberlearning

June 24, 2008

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"Any opinions, findings, conclusions and recommendations expressed in this report are those of the Task Force and do not necessarily reflect or represent the views of the National Science Foundation."

Fostering Learning in the Networked World: The Cyberlearning Opportunity and Challenge

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Executive Summary

Imagine a high school student in the year 2015. She has grown up in a world where learning is as accessible through technologies at home as it is in the classroom, and digital content is as real to her as paper, lab equipment, or textbooks. At school, she and her classmates engage in creative problem-solving activities by manipulating simulations in a virtual laboratory or by downloading and analyzing visualizations of real-time data from remote sensors. Away from the classroom, she has seamless access to school materials and homework assignments using inexpensive mobile technologies. She continues to collaborate with her classmates in virtual environments that allow not only social interaction with each other but also rich connections with a wealth of supplementary content. Her teacher can track her progress over the course of a lesson plan and compare her performance across a lifelong “digital portfolio,” making note of areas that need additional attention through personalized assignments and alerting parents to specific concerns. What makes this possible is *cyberlearning*, the use of networked computing and communications technologies to support learning. Cyberlearning has the potential to transform education throughout a lifetime, enabling customized interaction with diverse learning materials on any topic—from anthropology to biochemistry to civil engineering to zoology. Learning does not stop with K–12 or higher education; cyberlearning supports continuous education at any age.

Citizens in all fields need to understand how science and technology affect policy, business, and personal decisions. The shortage of trained scientists and engineers is a small indicator of a much larger problem: insufficient knowledge and understanding about science and technology across our population. The educational system must respond dynamically to prepare our population for the complex, evolving, global challenges of the 21st century. Advances in technology are poised to meet these educational demands. Cyberlearning offers new learning and educational approaches and the possibility of redistributing learning experiences over time and

space, beyond the classroom and throughout a lifetime. We believe that cyberlearning has reached a turning point where learning payoffs can be accelerated. We also believe that this moment could be fleeting because, without deliberate efforts to coordinate cyberlearning approaches, we will miss the opportunity to provide effective support for the convergence of learning and technology. The National Science Foundation (NSF) is in a position to stimulate research and development that can enable this process.

Cyberlearning has tremendous potential right now because we have powerful new technologies, increased understanding of learning and instruction, and widespread demand for solutions to educational problems. In the last decade, the design of technologies and our understanding of how people learn have evolved together, while new approaches to research and design make the development and testing of technologies more responsive to real-world requirements and learning environments. NSF has played a key role in these advances, funding interdisciplinary programs specifically to support research and activities in the area of cyberlearning. NSF can continue to lead this revolution by leveraging its investments in the productive intersections between technology and the learning sciences.

Several factors have come together to open these opportunities for cyberlearning. Web technologies enable people to share, access, publish—and learn from—online content and software, across the globe. Content is no longer limited to the books, filmstrips, and videos associated with classroom instruction; networked content today provides a rich immersive learning environment incorporating accessible data using colorful visualizations, animated graphics, and interactive applications. Alongside these technology improvements, “open educational resources” offer learning content and software tools that support search, organization, interaction, and distribution of materials. Private companies are investing in projects to make

pervasive learning technologies more affordable and accessible. The global scope of networked educational materials, combined with “recommendation engine” software, helps individuals find special, niche content that appeals to their needs and interests. New models of remote data and application storage combined with broadband network access allow wireless, mobile computing, not just with laptop computers but also with cellular phones. Internet-telephony, videoconferencing, screen sharing, remote collaboration technologies, and immersive graphical environments make distributed collaboration and interaction much richer and more realistic. Even though schools have not yet fully joined this vibrant, digital world, information and communication technologies are deeply entwined in the lives of young learners. Cyberlearning thus offers a receptive audience a mix of diverse content via the combined technological capabilities of the Internet, high performance computing, advanced networking, in-home electronics, and mobile communications.

The Task Force on Cyberlearning was charged jointly by the Advisory Committees to the Education and Human Resources Directorate and the Office of Cyberinfrastructure to provide guidance to NSF on the opportunities, research questions, partners, strategies, and existing resources for cyberlearning. This report identifies directions for leveraging networked computing and communications technology. It also calls for research to establish successful ways of using these technologies to enhance educational opportunities and strengthen proven methods of learning. To offer recommendations that are within the scope of NSF’s charter, we focus on the STEM disciplines (science, technology, engineering, and mathematics) and the social, behavioral, and economic sciences based in the US.

Cyberlearning requires a coherent, supportive infrastructure. In this report, we identify eight core strategies that NSF can pursue to effectively promote the growth of a cyberlearning

infrastructure. These strategies and their associated research questions will need to be reviewed, updated, revised, and evaluated regularly. Overall, these strategies focus on promoting and leveraging new talent and new technological developments in the field of cyberlearning. The strategies encourage proactively addressing potential problems and opportunities associated with the responsible use of data, the reapplication of software tools and educational resources, and the scaling of technology for larger end-user communities. NSF should promote consideration of the ways that cyberlearning can transform STEM disciplines and K–12 education—both how technologies allow new ways of looking at and understanding content and how teachers can interact with students and their school assignments. Finally, the Task Force considers it essential to find creative means of sustaining cyberlearning innovations beyond their initial development cycle.

We also identify seven special opportunities for action that we feel have the greatest short-term payoff and long-term promise among the many that NSF might pursue. These opportunities tap into the potential of technologies to coordinate learning across multiple contexts, to connect students with remote and virtual laboratories, and to access virtual or “mixed reality” environments for interactive exchanges. The use of cyberlearning technologies also introduces specific issues that require prompt action. For example, NSF policies can play a role in guaranteeing that open educational resources are truly open and available for future use. The growing abundance of data is another key concern. Students and teachers alike need to be taught how to manage large amounts of data, whether produced through scientific research or collected as part of a student’s educational history. Perhaps most importantly the NSF directorates need to recognize cyberlearning as a pervasive NSF-wide strategy by funding the development of resources that can be used for both research and education.

Recommendations

We have identified five recommendations that cut across the strategies for growth and opportunities for action detailed in the body of the report. These recommendations offer initial steps for the NSF to take while complementing existing work at NSF:

- 1. Help build a vibrant cyberlearning field by promoting cross-disciplinary communities of cyberlearning researchers and practitioners** including technologists, educators, domain scientists, and social scientists. NSF can advance their insights through the publication of promising practices and the ongoing recruitment of diverse talents to carry the field forward.
- 2. Instill a “platform perspective”—shared, interoperable designs of hardware, software, and services—into NSF’s cyberlearning activities.** An effective platform should incorporate promising innovations from newly funded technology projects and offer fully tested and supported modules for use in classrooms. It should ensure that learning materials targeted for the platforms are widely useable and remain useable over time. The ongoing evolution of platform designs should be guided by an expert panel.

Two NSF resources merit specific attention: the National STEM Digital Library (NSDL) and the Innovative Technology Experiences for Students and Teachers (ITEST). Both resources should be reviewed in the context of recent and new developments in cyberinfrastructure and cyberlearning at NSF and with consideration of the other changing technological, social, and economic environments identified in this report.

- 3. Emphasize the transformative power of information and communications technology for learning, from K to grey.** Technologies that allow interaction with scientific data, visualizations, remote and virtual laboratories, and human expertise offer opportunities for additional research and broad implementation, particularly among the STEM domains. New information tools that seamlessly bridge multiple learning environments and technologies likewise deserve more research attention. In addition, teachers’ professional development should be supported through training programs, professional societies, and ongoing collaboration on the creation of new teaching materials.
- 4. Adopt programs and policies to promote open educational resources.** Materials funded by NSF should be made readily available on the web with permission for unrestricted reuse and recombination. New grant proposals should make their plans clear for both the availability and the sustainability of materials produced by their funded project.
- 5. Take responsibility for sustaining NSF-sponsored cyberlearning innovations.** Educational materials and learning innovations need to flourish beyond the funding of a grant. They can be maintained and extended across NSF divisions and through partnerships with industry, professional organizations, and other institutions.

In conclusion, widespread access to technology, increasingly sophisticated tools, and advances in understanding of how individuals learn combine to provide a stunning opportunity to transform education worldwide. We call for research, development, and proof-of-concept studies to tackle this massive challenge, to marshal energies from diverse communities, and to establish a vision for the future. Our hope is that this report stimulates the imagination and builds on the enthusiasm that we felt in preparing it.



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1. Introduction

To address the global problems of war and peace, economics, poverty, health, and the environment, we need a world citizenry with ready access to knowledge about science, technology, engineering, and mathematics (STEM); social, behavioral, and economic sciences; and the humanities. Our primary, secondary, and higher educational systems in the United States today lack the capacity to serve the full populace effectively, not to mention support the lifelong learning essential for coping with our rapidly evolving world. While technology cannot solve all the world's educational challenges and crises, it has the potential to broaden educational opportunities, improve public understanding, and strengthen learning in classrooms and beyond. This report identifies directions for leveraging networked computing and communications technology and calls for research to establish successful ways to use these technologies to enhance educational opportunities—by strengthening proven methods of learning and innovating to create new learning environments that transform and improve learning.

The Nation is at a crossroads. The Internet has matured sufficiently to support sophisticated tools, content, and services for most of the U.S. population and for a growing portion of the rest of the world. High-performance computing and advanced networking are ubiquitous not only in scientific research but in commodity services—such as Google, Facebook, and YouTube—and in personal technologies—such as computers, cell phones, personal digital assistants (PDAs), and game consoles. Most individuals (children and adults) in the United States and other developed countries now have cell phones, a technology that already is a dominant form of communication in the developing world. As the capabilities of these devices expand, they are becoming a viable educational platform, complementing those of laptop and desktop computing. Based on the development and widespread adoption of these technologies, we can anticipate that new innovations will continue to be introduced over the coming decade and continually reconfigure the realm of possibilities for learning in a

networked world.

Today, learners everywhere need to increase their knowledge and capabilities to keep pace with scientific advances and succeed in the global workplace. Traditional forms of education cannot meet this demand—simply to meet the worldwide needs for higher education, a major university would have to open every week (Atkins, Brown & Hammond, 2007). Widespread access to technology, increasingly sophisticated tools, and advances in understanding how people learn combine to provide a stunning opportunity to transform education worldwide.

While this is hardly the first report to call for action on improving access to learning through distributed technology (Ainsworth, Honey, Johnson et al., 2005; Atkins et al., 2007; Pea, Wulf, Elliot et al., 2003), the window of opportunity for action is here and now. We call for research, development, and proof-of-concept studies to tackle this massive challenge, to marshal energies from diverse communities, and to establish a vision for the future.

1.1 Charge to the Task Force

The Task Force on Cyberlearning was charged jointly by the Advisory Committees to the Education and Human Resources Directorate and the Office of Cyberinfrastructure to provide guidance to the National Science Foundation (NSF) on the following topics:

- What are the areas of new opportunity and great promise in cyberlearning?
- What are the key research questions related to cyberlearning? How might NSF work with the research and education communities to develop consensus around these questions?
- Who are the key partners that should be involved in this discussion and how do we ensure their ideas are heard?
- How should NSF proceed in developing a strategic approach to cyberlearning? What are the next steps?
- How do current activities such as the

National STEM Digital Library (NSDL) and the Innovative Technology Experiences for Students and Teachers (ITEST) program fit in the context of this larger vision? How can they be improved?

In forming our recommendations, we were asked to consider visions and recommendations from recent reports on cyberlearning and to identify potentially transformative opportunities in which NSF as a whole might invest.² As the task force was given only 6 months to research and write this report, we were asked to rely primarily on published sources, on the expertise of our membership, and on informal interaction with our network of experts in gathering information. We did not hold public hearings, as would be the case with a Blue Ribbon Panel, which normally has 2 years to conduct its proceedings.

1.2 Scope of Work

Our scope of work spans the STEM disciplines (science, technology, engineering, and mathematics) and the social, behavioral, and economic sciences as they intersect with education and the learning sciences, all of which are within the NSF charter. The arts and humanities are outside the scope of this report only because they are outside the charge of NSF. Similarly, our focus is primarily domestic, as that is NSF's first responsibility. That said, we expect many of our findings and recommendations to apply to the arts and humanities and to complement reports in those areas (Horrigan, 2008a; Unsworth, Courant, Fraser et al., 2006). Our findings also reflect and complement global concerns for learning with information technology (*e-Learning and Pedagogy*, 2006; Atkins et al., 2007; Pea et al., 2003).

The task force was presented initially with the term "cyber-enabled learning," which came from several workshops and a report on "Cyber Enabled Learning for the Future" (Ainsworth et al.,

2005). We found, however, that use of this term was largely confined to NSF reports. Instead, we coined the term "cyberlearning," defined as follows:

Cyberlearning: learning that is mediated by networked computing and communications technologies.

The choice of the term is deliberately parallel to "cyberinfrastructure," a term coined at NSF³ and now widely used there and elsewhere. In the foundational NSF report, it is defined only by example, emphasizing the integrative, collaborative, and distributed nature of new forms of research: "technology . . . now make[s] possible a comprehensive 'cyberinfrastructure' on which to build new types of scientific and engineering knowledge environments and organizations and to pursue research in new ways and with increased efficacy" (Atkins, Droegemeier, Feldman et al., 2003, p. 31). Despite the title, *Revolutionizing Science and Engineering Through Cyberinfrastructure*, the report explicitly states that the scope of cyberinfrastructure extends to all academic disciplines and to education.

NSF has invested heavily in cyberinfrastructure technologies, such as high-performance computers and telecommunications networks, and capabilities such as access to remote resources and services, and modeling and simulation. Cyberinfrastructure has become central to the NSF vision as a means to conduct new kinds of research and to foster new frontiers of learning by society in the sciences and all other disciplines (*Cyberinfrastructure Vision for 21st Century Discovery*, 2007). Our call in this report is for a parallel investment in cyberlearning that will make new kinds of learning possible in all disciplines. Cyberlearning offers new learning and educational approaches via networked computing and communication technologies, and the possibility of redistributing learning experiences over time and space. Our scope incorporates the entire range of learning

² NSF has described transformative opportunities as an institutional priority for the United States to remain competitive in the global economy and to contribute to the progress of science as a whole. Such opportunities are often high risk, but yield great returns. NSF has formulated an initiative in support of such research: (Enhancing Support of Transformative Research at the National Science Foundation, 2007).

³ Ruzena Bajcsy coined the term "cyberinfrastructure" in 2001 when she was NSF Associate Director for Computer and Information Science and Engineering to charge the Blue Ribbon Panel on Cyberinfrastructure (Freeman, 2007).

experiences over the course of a lifetime—not only formal education, not only in classes, but throughout the waking hours (Bransford, Vye, Stevens et al., 2006). We are concerned principally with cyberlearning as “learning with” cyberinfrastructure, rather than “learning about” cyberinfrastructure. The latter concern for building a scientific workforce is addressed in the NSF Vision document, (*Cyber-infrastructure Vision for 21st Century Discovery*, 2007).

Our use of the term “cyberlearning” is intended to evoke both cyberinfrastructure technologies and

theoretical connections to cybernetics. Norbert Wiener’s (1948) foundational choice of the “cyber” prefix for the field of cybernetics built etymologically on the Greek term for “steering” as a way to signal the intertwined tapestry of concepts relating the goal-directed actions, predictions, feedback, and responses in the systems (physical, social, engineering) for which cybernetics was to be an explanatory framework. Cyberlearning is thus learning in a networked world, where the forms of “steering” of learning can arise in a hybrid manner from a variety of personal, educational, or collective sources and designs.

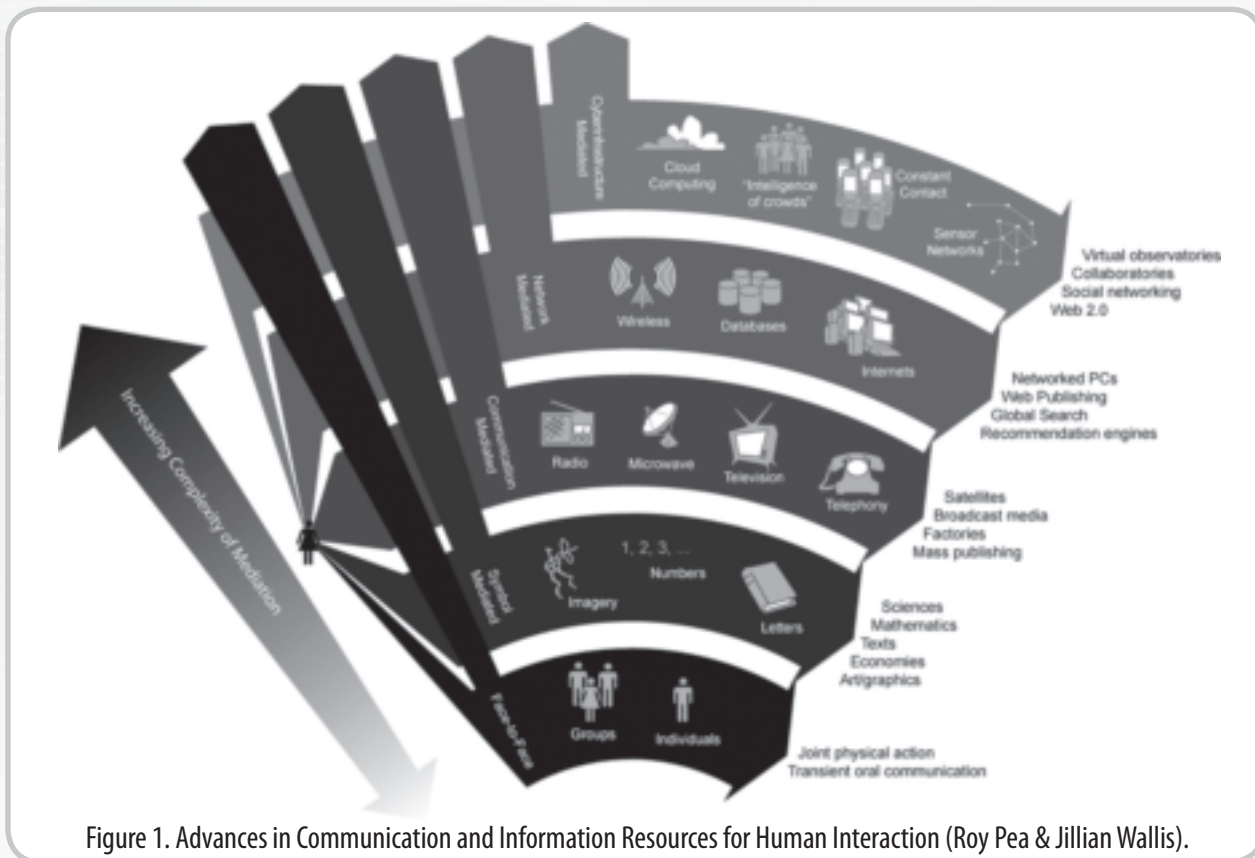


Figure 1. Advances in Communication and Information Resources for Human Interaction (Roy Pea & Jillian Wallis).

Figure 1 depicts historical advances in the communication and information resources available for human interaction. Basic face-to-face interaction at the bottom level requires no resources to mediate communication. The second wave of resources offered symbol systems such as written language, graphics, and mathematics but introduced a mediating layer between people. The communication revolution of radio, telephony, television, and satellites was the third wave. The outcomes of the fourth wave—networked personal computers, web publishing, and global search—set the stage for the fifth wave of cyberinfrastructure and participatory technologies that are reviewed in our report. In sum, the set of actions and interactions people consider possible has changed with each new wave of mediating technologies, from writing to telephony to the Internet and now cyberinfrastructure. We can now interact at a distance, accessing complex and useful resources in ways unimaginable in early eras.

1.3 Why Cyberlearning and Why Now?

A Nation Still at Risk

Twenty-five years after the U.S. Department of Education report, *A Nation at Risk*, stirred the country to action in response to the sorry state of public education, the situation is little changed. President Reagan's charge to that task force in 1982 has yet to be accomplished:

This public awareness—and I hope public action—is long overdue. . . . This country was built on American respect for education. . . . Our challenge now is to create a resurgence of that thirst for education that typifies our Nation's history (*A Nation at Risk*, 1983).

Few of the innovations tried over the ensuing 25 years have resulted in large-scale systemic change in education. Despite the revolutions wrought by technology in medicine, engineering, communications, and many other fields, the classrooms, textbooks, and lectures of today are little different than those of our parents. Yet today's students use computers, mobile telephones, and other portable technical devices regularly for almost every form of communication except learning. The time is now—if not long overdue—for radical rethinking of learning and of the metrics for success. Education and learning are not the same thing, nor are schools the only venue for learning. Our concern in this report is to promote “a resurgence of thirst” for learning and to assess the potential of cyberlearning to accomplish that goal. While reforming the public school system is well beyond the scope of our present task force, positive effects on schooling would certainly result from invigorating and inspiring learners through the rich new environments made possible by the Internet and developments in cyberinfrastructure.

Despite U.S. leadership in higher education for science and engineering, the Nation faces a continuing shortage of scientists and engineers. The Nation also needs citizens in all careers who are sufficiently knowledgeable about science and technology to make informed choices about

public policy, business opportunities, and personal activities that involve science and technology. Major opportunities for improving learning at all levels of education, from K to gray, are the focus of this report. As a leading funder of scientific research and a heavy investor in science education at the postsecondary levels, NSF is in a strong position to effect substantial and reasonably rapid change in higher education. Truly new opportunities exist to reach people of all ages outside of the traditional K–12 and higher education systems, including adult learners of all kinds. Given the need for greater knowledge about science and technology throughout the population, these nontraditional educational opportunities are of great potential importance, and NSF can play a leadership role here as well. Note that the National Institutes of Health (working in part through the National Library of Medicine) have similarly taken on a major role in recent years in patient education and education of the broad public about health matters.

Radical change rarely is instantaneous. Rather, underlying sudden changes are long and persistent investments. The “productivity paradox” is the obvious analogy for cyberlearning. Despite the reports of economists, sociologists, and policymakers that technology was having minimal payoff in worker productivity (Harris, 1994; Kraut, Kiesler, Boneva et al., 2002; Tijssen & van Wijk, 1999), industry, government, and academe continued their research and development in information technology. By the early part of the 21st century, the tide had turned. The Internet had “come of age,” and we turned our attention to ways in which it could be used to enhance innovation and creativity (Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers 2001; The Internet's Coming of Age, 2001; Mitchell, Inouye & Blumenthal, 2003). In today's business world, “value is shifting from products to solutions to experiences” (Pralhad & Krishnan, 2008, p. 24). Today's learners live in that online experiential environment; today's schools do not. Investments must be made now, while a new generation of learners can be reached where they are now—their lives deeply entwined with communications

technologies—before they diverge yet further from today’s educational methods. We believe that cyberlearning has reached the inflection point where real learning payoffs can be achieved. We also believe that this moment could be fleeting if we fail to take advantage of this window of opportunity.

Both cyberinfrastructure and the learning sciences are areas of high priority and significant investment for NSF,⁴ yet little attention has been paid to the productive intersections between them. It is imperative that NSF establish a coherent approach to cyberlearning to enable the transformational promise of technology for improving educational opportunity. Toward that end, this report addresses the most promising areas for investment and recommends that NSF assess the current portfolio and identify points of leverage and enhancement.

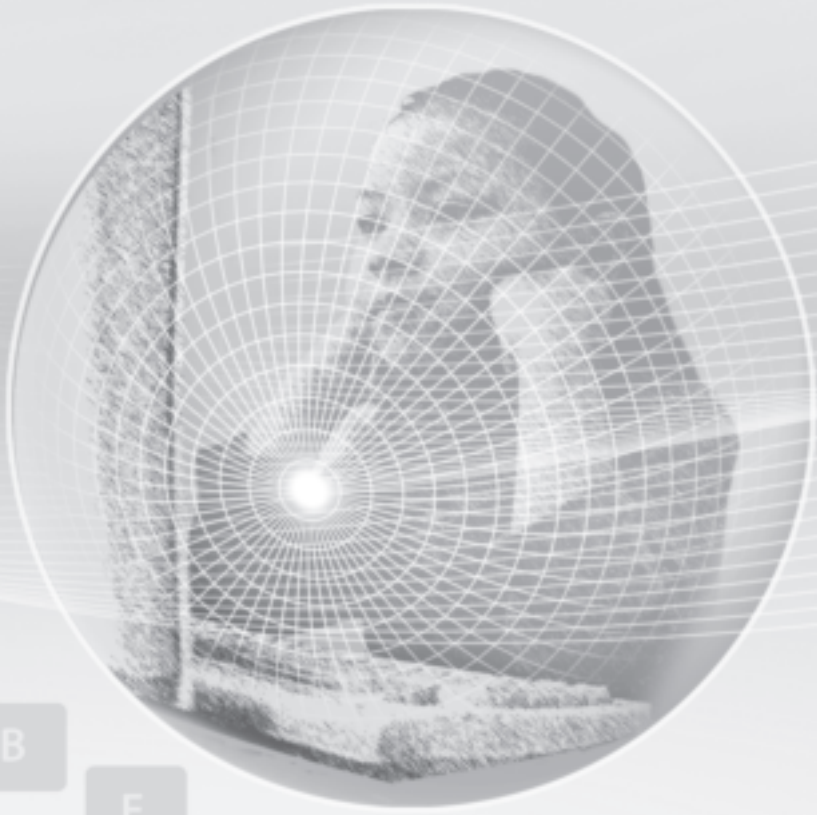
Accomplishing such a transformation requires significant change in the processes of learning. Research and field deployments have demonstrated how incorporating information and communications technologies into science and mathematics can restructure the necessary expertise for reasoning and learning in these domains, in effect opening up greater access to complex subject matter—for example, multiple linked representations in calculus and algebra (Kaput, Hegedus & Lesh, 2007); uses of agent-based modeling as an approach to understanding complexity sciences (Wilensky & Reisman, 2006); uses of scientific visualization for investigating complexity science topics (Edelson, Gordin & Pea, 1999; Linn, Lee, Tinger et al., 2006; McKagan, Perkins, Dubson et al., 2008; Pea, 2002).

Cyberlearning offers opportunities to be on the frontier of technical, social, learning, and policy research. Information technology has the potential to close knowledge gaps, but also to widen those gaps as new digital divides appear with each wave of technical innovation. The challenge is to create a dynamically evolving system to support the learning requirements of

21st century society, work, and citizenship—from K–12 to higher education and beyond to lifelong learning (Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, 2007).

We frame this report in the context of current and predicted technological and educational environments of 21st century learners. In subsequent sections we identify strategies for building a cyberlearning infrastructure and opportunities for action by NSF (both specific and general); we conclude with our overall set of recommendations.

⁴ Appendix 3 is a list of NSF reports relevant to cyberlearning.



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2. Background:

How We Got Here and Why Now

We reflect briefly on the current state of information technologies for learning and the many strands of prior research that have created the conditions for the major new waves of innovation possible today. A strategic cyberlearning focus by NSF will build upon this history.

2.1 Technology and Educational Environments of 21st Century Learners

Why is this such a propitious time for a cyberlearning initiative? How can we build productively on what has been learned before? A cluster of interacting factors have contributed to the flowering of this new opportunity and challenge:

- **A new participatory Web culture.** New Web functionalities during the past several years have made participatory media culture a reality, contributing to the personal, professional, and educational lives of learners (Jenkins, 2006; Jenkins, Clinton, Purushotma et al., 2006). In less than 3 years, the public video upload site YouTube has become the third most trafficked Web site in the world, with 2.9 billion video streams viewed in February 2008 (*Who's Watching What Video Online and Where: Results from Nielsen Online*, 2008). Increasingly, such capabilities are being used for education as well as informal learning. Hundreds of millions of people, and large proportions of the U.S. population, from middle school to adults, publish blogs, photos, videos, book reviews, social profiles, useful bookmark lists, and other content online for others to use and learn from. (See the many Pew Internet and American Life Project reports.) An important characteristic of such rapid adoption of these platforms is continuous beta releases that improve constantly from user feedback.

- **The ease of deploying software at Web scale.** The emergence of the Web over the 1990s brought with it an astonishing capability: virtually anyone could publish data on a global scale. This was a radical change from the pre-Web era, and

our social institutions are still digesting the consequences. This ability is rooted in basic principles of Web architecture (Jacobs & Walsh, 2004): all information resources are linked together with the same linking mechanism (interoperability), and publishers do not need permission to create links (openness). Shortly after the turn of the century, information technologists began to demonstrate that the same principles permitting data access at Web scale can also apply to programs. With Web service architectures, developers can deploy software components and services that are accessible from any Web browser. There are now several popular Web application development platforms—both proprietary, such as Microsoft's .NET, and open source, such as the Linux/Apache/MySQL/Perl (LAMP) suite. With these platforms, just as anyone can publish content at Web scale, anyone can create software programs and make them immediately accessible to a global audience. Very recently, initiatives like Amazon's Web Services and Google's App Server have begun making scalable Web hosting infrastructures openly available to all Web developers. As a result, the development gap between small-scale testing of Web programs and massive-scale deployment is vanishing. It is no longer necessary to make large financial investments to have a huge impact in deploying software on the Web.

- **Open educational resources.** "Open educational resources" (OER) was first adopted as a term at UNESCO's 2002 Forum on the Impact of Open Courseware for Higher Education in Developing Countries, funded by the William and Flora Hewlett Foundation (Atkins et al., 2007). OER are educational materials and resources offered without cost for anyone to use anytime and under a license to remix, improve, and redistribute. It includes learning content at different levels of granularity for students and teachers at all levels of learning, including videos, books, lesson plans, games, simulations, and full courses and open-access content; open-source software tools that support the creation, delivery, use, and improvement of open learning content, including searching and organization of content;

content and learning management systems (e.g., Moodle, Sakai); online learning communities; and intellectual property licenses (e.g., Creative Commons) to promote open materials publishing, design principles, and content localization. Open-source course management systems are being deployed widely in universities, and to some extent in K–12.⁵ OpenCourseWare (OCW), initiated in 2002 by Massachusetts Institute of Technology (MIT), publishes free, extensive materials about 1,800 courses, including syllabi, lecture notes and often complete lectures, assessments, readings, and so on. Since 2002, more than 100 other universities from all over the world have published their own materials and formed the OCW Consortium. Hundreds of open full courses—including lecture courses from Yale, Berkeley, and MIT; suites of multimedia courses, and cognitive tutor courses from Carnegie Mellon—populate the Web and serve secondary schools as well as universities. In the developing world, the OER movement has been immensely well received as these countries work to broaden their access to education and, simultaneously, improve its quality.

• **From mass markets to millions of niches.** The “Long Tail” marketplace phenomenon, as popularized by *Wired* magazine editor Chris Anderson (2006), refers to the new business models made possible by distributed access to consumers and products. Web-based companies such as Amazon, Netflix, and Apple iTunes have realized new kinds of profits by selling small volumes of hard-to-find items to a large number of buyers. Anderson characterizes the need of brick-and-mortar businesses, which are constrained by shelf space, to sell large volumes of a small number of popular items, as the “hits” business model. The Long Tail refers to the populace under the distribution curve who purchase harder-to-find items, and the reachable market size, it is argued, has grown in some cases by a factor of two or three compared with physical retailing locations because of the new long tail dynamics of Web purchasing. A key

technological capability that makes the Long Tail model work is the success of data-driven “recommendation engine” software (Resnick & Varian, 1997), which uses the aggregated purchasing and browsing patterns of users to guide those who follow them to find items that they may like. Many Amazon book purchases come via this route, and more than 60 percent of Netflix video rentals come from such recommendations, which drive demand down the long tail.⁶ The relevance of Long Tail phenomena to education and cyberlearning is evident: learning trajectories, whether for STEM or other content, no longer need be constrained to the “hits” now represented by published textbooks and traditional pedagogical channels. As the costs of online publishing go down, the quality of learning object metadata improves, and search engines make it easier to find learning niche content, a different ecosystem of learning materials will evolve. Libraries already are finding vast new audiences for the old and obscure material now being digitized, and are distinguishing themselves in the marketplace of ideas by expanding access to their special collections.

• **Ubiquitous computing, mobiles, and broadband networking.** More and more frequently, learners have access to one or more of their own computers for learning, more commonly at home but also at school. The Pew Internet and American Life Project currently estimates that 75 percent of adults and 90 percent of teenagers in the United States go online, and 80 percent of adults have a cell phone. There are more than 1 billion computer users in the world, with predictions of 2 billion users by 2015,⁷ and 3.5 billion mobile phone subscribers,⁸ with emerging mobile phone technologies already sharing many of the functionalities with laptop computing. A recent Pew Internet and American Life Project report (Horrigan, 2008a) states that 62 percent of all Americans now participate as part of a wireless, mobile population in digital activities away from home or work, with youth particularly

5 For examples of K–12 implementation case studies, see <http://www.k12opentech.org/implementation-study-3-moodle>.

6 Netflix ships almost 2 million DVDs per day to its 8 million customers, and has more than 2 billion movie ratings contributed by its members about more than 9,000 full-length movies and television episodes.

7 See <http://tinyurl.com/yvbw32>.

8 See <http://tinyurl.com/3xgsk6> and <http://tinyurl.com/3cmmfr>.

attuned to new access. African Americans and English-speaking Latinos are more likely than white Americans to use nonvoice data applications on their cells. Furthermore, another Pew report concludes, “With the Federal Communications Commission auctioning spectrum well-suited for high-speed wireless applications, and with some companies beginning to open up handheld devices to application developers, more innovations in wireless access are on the horizon. In particular, ‘cloud computing’ will emerge in the coming years—moving applications and data storage away from the desktop or laptop to remote servers managed by high-speed networks. Computing applications and users’ data archives will increasingly be accessible by different devices anytime, anywhere over fast and widely available wireless and wired networks. It is hard to overstate the importance of online access becoming decoupled from desktop computing” (Horrigan, 2008b). With such networked devices as computers and mobile phones come the benefits of Metcalfe’s Law (Gilder, 1993)—the value of a communications network grows exponentially with growth in the number of users (e.g., the Internet, the Web, social networking).

• **New collaborative modes, media richness, and virtual worlds.** Today distributed teams in research laboratories, businesses, and education can collaboratively conduct their activities using Internet telephony, videoconferencing, and screen sharing and be “together” in immersive graphic worlds. Scientific work further incorporates shared data repositories, software data-analytic workbenches, and remote instrumentation in collaboratories (Bos, Zimmerman, Olson et al., 2007). The increasing prevalence of broadband networking access (half of American adults now have broadband access at home) has also made possible distributed high-resolution multimedia learning, gaming environments, and participatory media culture contributions. Finally, advances in computer graphics, interactive visualizations, and immersive technologies now provide verisimilitude to the physical world, a window on unseen processes, and support for hypothetical explorations.

2.2 A Cyberlearning Infrastructure Based on Knowledge About Learning

How can the potential of cyberlearning be realized? NSF has funded pioneering research and development in learning and teaching technologies for most of its existence. And of course its contributions to the development of the Internet, to Web browsers, to high-performance computing and communications, and to other core enabling technologies of the present global cyberinfrastructure have helped pave the way for these cyberlearning opportunities (The Internet’s Coming of Age, 2001; *A Brief History of NSF and the Internet*, 2003). New technologies follow complex trajectories often supported or thwarted by other technologies, infrastructural issues, competing standards, social systems, political decisions, and customer demands. Vacuum tubes and transistors are good examples: vacuum tubes were initially developed for radios but spurred the development of televisions and mainframe computers. Transistors transformed all these applications and led to completely new opportunities, including portable computing devices. The history of these innovations is littered with failures, dead ends, abandoned standards, and phenomenally creative inventions.

Learning technologies build on these innovations and also need to interface with complex social systems, including families, schools, and political decisionmakers. From early efforts to create electronic books to current efforts to design online courses, initial attempts to use new technologies require extensive trials and refinement before they succeed. Often early designs fail because they do not realize the full potential of the technology, as is typical of early technologies. Often innovations that succeed in one learning context need customization to work in another. In education, we are only now benefiting from advances in scientific understanding of how people learn (Sawyer, 2006), of what constitutes good teaching, and of which tests and indicators validly assess impact or predict future success. Cyberlearning has

tremendous potential right now because we have effective new technologies, increased understanding of learning and instruction, and widespread demand for solutions to educational problems.

A series of NSF and other federally funded contributions specific to learning and education have laid the groundwork for effective research in the area of cyberlearning (Being Fluent with Educational Technology, 1999; Ainsworth et al., 2005; Bransford, Brown & Cocking, 2000; Feurzig, 2006; Pea et al., 2003; Roberts, 1988; Roschelle, Pea, Hoadley et al., 2001; Zia, 2005). Numerous interdisciplinary, multidirectorate NSF programs in the past decade or so have contributed to the opportunity space for new cyberlearning activities. These include the following programs: Collaborative Research on Learning Technologies (CRLT) (Guzdial & Weingarten, 1996; Sabelli & Pea, 2004); Learning and Intelligent Systems (LIS) (Gentner, Linn, Narendra et al., 1995); Knowledge and Distributed Intelligence (KDI); Information Technology Research (ITR) (Cummings & Kiesler, 2007; Sabelli & DiGiano, 2003); the Interagency Educational Research Initiative (IERI), jointly with the U.S. Department of Education and National Institute of Child Health and Human Development, spawned by the President's Council of Advisors on Science and Technology 1997 report; Human and Social Dynamics (HSD); Sciences of Learning Centers (SLC); and the recent Advanced Learning Technologies (ALT) program.

These programs have developed the following successful products:

- Visual programming languages designed for children (DiSessa, 2000; Repenning, 2000; Smith, Cypher & Tesler, 2000)
- Microworlds for learning computational thinking in science, technology, engineering, and mathematics (DiSessa, 2000; Resnick, 1994; White, 1993)
- Intelligent tutoring systems in algebra, geometry, and programming (Koedinger & Corbett, 2006)

- Microcomputer-based laboratories and handheld computing versions of probeware and sensors for capturing and graphing data during scientific inquiry (Linn & Hsi, 2000; Mokros & Tinker, 1987; Resnick, Berg & Eisenberg, 2000; Rogers, Price, Fitzpatrick et al., 2004; Roschelle et al., 2001; Thornton & Sokoloff, 1990; Tinker & Krajcik, 2001)
- Online learning communities for teachers and learners in many subject domains (Barab, Schatz & Scheckler, 2004; Hiltz & Goldman, 2005; Palloff & Pratt, 2005; Pea, Gomez, Edelson et al., 1997; Polman, 2000; Schlager & Fusco, 2003; Shrader, Fishman, Barab et al., 2002; Steinkuehler, Derry, Woods et al., 2002)
- Data visualization environments for examining and understanding complexity in the STEM disciplines (Edelson et al., 1999; Linn et al., 2006; Pallant & Tinker, 2004)
- Scientific inquiry support environments in biology, chemistry, and physics (Blumenfeld, Fishman, Krajcik et al., 2000; Linn, Davis & Bell, 2004; Quintana, Reiser, Davis et al., 2004; Reiser, Tabak, Sandoval et al., 2001; Sandoval & Reiser, 2003)
- Educational robotics (Resnick, Martin, Sargent et al., 1996; Rusk, Resnick, Berg et al., 2007)
- STEM learning games and virtual worlds (Barab, Hay, Barnett et al., 2001; Barab, Thomas, Dodge et al., 2005; Dede, Salzman, Loftin et al., 2000; Nelson, Ketelhut, Clarke et al., 2005).

The previous works exemplify the potential of transformative technologies available from the 1970s to the beginning of the 21st century. These projects provided pioneering contributions in an era of stand-alone and early networked educational microcomputing in classrooms and introduced scientific inquiry incorporating real-time sensor data capture. A new generation of projects has brought to teaching and learning examples of the resounding power of the Internet and Web technologies, educational collaboratories, and interactive scientific visualizations to aid learners in understanding complex topics; online learning communities;

Web-based video learning for teacher professional development; and other advances that have leveraged network infrastructure capabilities. *A new generation of cyberlearning contributions promises greater pervasiveness and mobility, scale, cumulativity, and effectiveness in supporting the learning enterprise from K to gray.*

During the past decade, the sciences of how people learn and the design of technologies for supporting learning, teaching, and education have begun to productively coevolve. The interdisciplinary emphases of many of the aforementioned programs have helped spawn the kinds of productive collaborations that have brought learning scientists together with computer scientists, engineers, interaction designers, subject matter experts, social scientists with varied expertise, designers of assessments, and educators. The National Research Council's influential volumes on *How People Learn* (Bransford et al., 2000) and *Knowing What Students Know* (Pellegrino, Chudowsky & Glaser, 2001) have contributed to a research and partnership environment that is increasingly applying principles of learning and assessment in new learning and teaching technology designs.

The debate over scientific research in education and the U.S. Department of Education's focus in its Institute for Educational Sciences on randomized clinical trials as the gold standard for science have had significant influence. Recently, however, there is also a broad realization that rapidly changing technological environments and new workforce demands (*Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, 2007) call for new metrics and methodologies. The measures of student progress need to align with the skills required in school, the workforce, and life. The methodologies of design experiments and rapid prototyping play important roles in developing transformative advances for STEM learning and teaching, which iteratively adapt new tools to the needs of learning and teaching in the disciplines (Cobb, DiSessa, Lehrer et al., 2003; Design-Based Research Collective, 2003).

Educational research and practice now recognize how much the nature of learning and teaching is shaped by the properties of the systems and contexts in which such activities take place (Bransford et al., 2000; Shonkoff & Phillips, 1998). Researchers have studied teacher preparation, teacher learning, teaching standards, and teacher implementations of innovative curricula (Borko, 2004; Davis, Petish & Smithey, 2006). Investigators have begun to examine the nature of assessments (Heubert & Hauser, 1999); school leadership (Gerard, Bowyer & Linn, in press); and broader relationships between school, home, and community (Duschl, Schweingruber & Shouse, 2007).

As a result of these advances, it is time to strengthen the research programs supporting cyberlearning. These advances signal a new era for the role of technology in education. Whereas prior research has shown benefits for a few classrooms, a single school, or a single topic, we are now poised to conduct investigations in much more complex contexts. It is now possible to draw on more powerful technologies to design curriculum, support teachers, and monitor progress. These factors underscore the importance of funding research on cyberlearning to transform education. Many groups, including the National Mathematics Advisory Panel (*Foundations for success: Report of the National Mathematics Advisory Panel*, 2008) and the Committee on Prospering in the Global Economy of the 21st Century (*Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, 2007) have called for more large-scale, sustained, and systematic research on these opportunities to solve pressing educational problems.



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3. Strategies for Building a Cyberlearning Infrastructure

Knowledge about how people learn is a critical component of cyberlearning. Using this knowledge in the best way possible for life-long learners requires other components that, taken together, comprise a supportive cyber-infrastructure for learning. Infrastructures take many forms, including railroads, electric power grids, telephone, cellular services, and the Internet (Edwards, Jackson, Bowker et al., 2007; Friedlander, 1995a; b; 1996a; b; 2002a; b; 2005). They are complex structures that can take many years to build and are embedded deeply in other structures and social relationships (Star & Ruhleder, 1996). Scientists and scholars in all disciplines, the world over, are finding ways to ask new questions, deploy new methods, and exploit a far wider array of data through cyber-infrastructure-mediated research (Borgman, 2007). Considerations for infrastructure include building a field (human capital, networks, etc.); creating models of sustainability and interoperability; establishing design principles (modularity, appropriate for multiple devices, localizability, etc.); and exploring open platforms. The task of developing an infrastructure has goals and a set of strategies to achieve the goals. The goals represent a theory that describes a viable infrastructure. The goals and strategies will need to be reviewed, updated, revised, and evaluated regularly. Some of these goals (e.g., a strong and sustainable field) will take considerable time to achieve, while other goals [e.g., open-source platform(s)] will take less time, although continuous work in this area will be required owing to the rapid evolution of technology.

We define eight general strategies that we consider instrumental to NSF fulfilling this leadership prospect. Associated with each of the strategies are sets of research questions. The strategies are to (1) develop a vibrant, generative cyberlearning field; (2) instill a “platform perspective” into NSF’s cyberlearning programs; (3) generate and manage cyberlearning data effectively and responsibly; (4) target new audiences with cyberlearning innovations; (5) address cyberlearning problems at appropriate scales; (6) reexamine what it means to “know”

STEM disciplines with cyberlearning technologies; (7) take responsibility for sustaining NSF-supported cyberlearning innovations; and (8) incorporate cyberlearning in K–12 education. We see these strategies as mirroring the radical shifts in how society is exploiting information and communication technologies more broadly in business, society, and science—and *learning* needs to take reins of these changes as well. These strategies do not reflect business as usual, but an ambitious set of highly leveraged approaches for launching cyberlearning as a new enterprise.

These are by no means the only strategies that NSF might pursue in building a cyber-infrastructure for learning. We chose these eight strategies as important, engaging to a wide audience, amenable to clear plans of action, and responsive to the challenges of demonstrating proof of concept in a reasonable time period. In the following sub-sections we describe these strategies in more detail. Then, in Section 4, we present a set of cyberlearning activities that represent special opportunities for NSF.

3.1 Develop a Vibrant, Generative Cyberlearning Field

The new field of cyberlearning requires new forms of expertise, new collaboration skills, new kinds of public-private partnerships, as well as flexibility and agility in the planning and conduct of research, development, and funding. Preparing the next generation of cyberlearning leaders parallels the challenge NSF met for the field of nanotechnology. A similar approach is needed, including support for centers that bring the emerging leaders together to rapidly develop the field of cyberlearning. Cyberlearning has the added challenges of needing to leverage rapid industry developments and of developing a cyberliterate citizenry.

To develop a technologically literate citizenry, multiple opportunities to participate in the field, rich professional development approaches, leaders of the future, and new methods for research partnerships, the field needs the following:

- Precollege, undergraduate, and graduate courses that attract new talent, take advantage of cyberlearning tools, and impart the skills necessary to contribute to the field.
- Graduate and postdoctoral preparation programs such as multi-institutional centers to acculturate future leaders by enmeshing them in the research and development activities of the emerging cyberlearning community, including the widely varied stakeholders from academe, industry, education, and other contributors.
- Methods to attract and support new and established researchers in forming partnerships to tackle cyberlearning problems. We need to offer those interested in becoming involved in cyberlearning multiple ways to gain expertise in the field, while respecting their ideas and shaping their understanding. We need to support and reward partnerships of investigators who learn from each other and combine varied expertise to develop innovations (e.g., Sabelli & Pea, 2004).
- Creative funding mechanisms for attracting intensive and innovative contributions to the cyberlearning field, such as innovation inducement prizes (see *Innovation Inducement Prizes at the National Science Foundation, 2007*),⁹ which are considered to have the virtues of attracting diverse efforts and significant resources on a scientifically or socially worthwhile goal while leaving open how the goal will be achieved, and creating a ripple effect of beneficially broad interest in the objectives beyond the competitors.
- Intensive cyberlearning summer workshops

for faculty and advanced students that can quickly spread innovations and new research and design methodologies and techniques to build capacity in educational institutions across the national landscape.

Research Questions:

1. How can we leverage the best of cyberlearning advances in the universities and industry to attract and prepare a new, diverse generation of leaders?
2. How does cyberlearning change the nature of lifelong and lifewide learning?
3. Taking advantage of new ways to document progress, what are the varied pathways and trajectories that newcomers follow, and which ones are optimal?
4. What are effective forms of professional development to stimulate the field to build on the successes of others using open-source learning environments, platforms, and other community supports such as “cloud computing”?
5. What are promising methods for bridging international communities to form a vibrant, multinational field?

3.2 Instill a Platform Perspective Into NSF’s Cyberlearning Programs

Networked environments, including the Internet, World Wide Web, and cellular telephone systems, have made it possible for communities to emerge that create and use shared, interoperable services and platforms. These communities are innovative and entrepreneurial, and fast-moving by virtue of their scale and openness. This transformation has sparked the revolution in commerce over the past two decades. Innovations such as shared instrumentation, scientific databases, and grid computing are changing scientific research.

9 Traditions of scientific and innovation competitions from past centuries have been reenergized recently with prominent examples hosted by The X Prize Foundation: the Google Lunar X PRIZE (a \$30 million competition for the first privately funded team to send a robot to the moon, travel 500 meters, and transmit video, images, and data to Earth), the Progressive Automotive X PRIZE (a \$10 million competition to inspire new, viable, super fuel-efficient vehicles), and the Archon X PRIZE for Genomics (a \$10 million prize for creating a human genome sequencer that can sequence 100 individual genomes with an accuracy of more than 99 percent within 10 days, with each sequence costing \$10,000 or less). An NSF-funded NRC 2007 report concludes that “an ambitious program of innovation inducement prize contests will be a sound investment in strengthening the infrastructure for U.S. innovation. Experimental in its early stages, the program should be carried out in close association with the academic community, scientific and technical societies, industry organizations, venture capitalists, and others” (Innovation Inducement Prizes at the National Science Foundation, 2007).

Cyberlearning requires a common, open platform to support communities of developers and learners in ways that enable both to take advantage of advances in the learning sciences. The platform architecture must be designed so that it can evolve, especially over the coming decade as computing shifts come into their own. Thus, any platform design will perforce be an iterative exercise.

The potential for cyberinfrastructure requires a strategic outlook that promotes synergy and interoperability among cyberlearning innovations. The infrastructure can:

- Motivate the merging of promising innovations into a few unique, customizable resources. For example, rather than having many similar collaborative tools, we would like to stimulate the development of a small number of tools that offer distinct advantages or specific capabilities.
- Support an open community of developers who create resources that are open, interoperable, modular, and complementary. Such a community might be modeled after what has been learned about the Linux community (Raymond, 2001) or the Mozilla or Apache communities (Mockus, Fielding & Herbsleb, 2002) in that participants jointly build on promising innovations (Dalle, David, Ghosh et al., 2005).
- Create interoperable resources that support developers so that they can concentrate on their innovation and contribute to the community. Rather than expecting individual projects to take responsibility for all aspects of learning, developers should be able to test their ideas with available tools for such activities as recording student data, designing assessments, acquiring sensor data, or storing data that would be applicable to a wide variety of cyberlearning activities.
- Encourage designs of learning and educational innovations that build in knowledge about learning and instruction based on research and trials in classrooms or informal

environments such as museums. Such innovations might implement promising design principles or pedagogical patterns warranted by research results.

- Support innovations that lead to seamless learning across home, school, and other settings by building on emerging technologies such as social networking, community knowledge resources (e.g., wikis), and recommender systems (e.g., Ainsworth et al., 2005; Chan, Roschelle, Hsi et al., 2006).

The potential for cyberlearning will best be achieved with open-source design projects. The field will advance with the emergence of shared software components, analysis, training, and dissemination activities, as is possible with a common open cyberlearning platform.

Of all the transformational catalysts brought by the Internet and the Web as technology infrastructures, *perhaps the most fundamental is that innovators and entrepreneurs can draw upon shared, interoperable services and platforms.* This transformation has been at the heart of the revolution in commerce over the past two decades. The emergence of a common platform has sparked a revolution in science through initiatives based on large-scale shared instrumentation, scientific databases, and grid computing. Likewise, the potential for cyberinfrastructure in learning can be realized only by adopting a strategic outlook that promotes synergy and interoperability among cyberlearning innovations, by drawing upon common resources and services. This might require targeting separate funding to “horizontal” efforts that cut across “vertical” innovations, rather than expecting individual projects to take responsibility for all aspects of an innovation. As an example, rather than funding projects to perform individual assessments of their work, NSF might fund the creation of a set of assessment tools and services that would be applicable to a variety of cyberlearning activities, and then require projects to participate in that assessment. Similar comments apply to encouraging the emergence of shared software components,

analysis, training, and dissemination activities, as delineated below in the recommended initiative on a common open cyberlearning platform.

The platform for cyberlearning will not be monolithic. Rather, we expect that multiple platforms at different levels, and for different purposes, will be required. The architecture through which these platforms relate and through which their coevolution can occur is a complex research challenge in its own right. Work already accomplished in defining relevant standards for commercial and open-source software platforms may underpin the platform perspective for cyberlearning. Notable here are standards, best practices, and policy work on Learning Management Systems (a.k.a. Course Management Systems or Virtual Learning Environments) under the auspices of groups such as the Instructional Management System Project (and earlier, the Educause National Learning Infrastructure Initiative), the Moodle and Sakai projects, and a wide range of research and development efforts on immersive and 3D environments.

Research Questions:

1. How can we merge innovations and create community resources?
2. How can we encourage collaborative development and enhancement of innovations created by others? What are appropriate criteria and standards?
3. How can we incorporate advances in learning sciences into authoring curriculum, assessment, and other materials to appropriately scaffold learning processes?
4. What are effective ways to establish the educational validity of innovative approaches to instruction?
5. What are principles of interoperability for promoting synergy across cyberlearning technologies and—more important—across practices that harness cyberlearning to address national priorities?
6. What is the architecture of the platforms

needed to support cyberlearning, and how do its features relate to work already complete or under way?

3.3 Generate and Manage Cyberlearning Data Effectively and Responsibly

3.3.1 The Two Data Deluges: Opportunities and Threats

Among the greatest benefits—and challenges—of cyberinfrastructure is the deluge of scientific data (*Cyberinfrastructure Vision for 21st Century Discovery*, 2007; Borgman, 2007; Hey & Trefethen, 2003; Hey & Trefethen, 2005). Today's highly instrumented science and engineering research is generating data at far greater rates and volumes than ever before possible. In addition, as more human communication takes place in the networked world for education, commerce, and social activity, an extensive digital trace is being created, a deluge of behavioral data. These data are extremely valuable for modeling human activity and for tailoring responses to the individual—whether for learning or for commerce. While these vast amounts of data allow scholars to ask new questions in new ways, and teachers to assess learning in new ways, they also pose a wide range of concerns for management, preservation, access, intellectual property, and privacy, especially in the cases of educational, social, behavioral, and economic sciences and medical records (e.g., Agrawal & Srikant, 2000; Derry, 2007; Gross, Airoidi, Malin et al., 2005; Madden, Fox, Smith et al., 2007; Newton, Sweeney & Malin, 2005; Schafer, Konstan & Riedl, 2001; Sweeney, 2002; 2005).

3.3.2 Produce, Use, and Reuse Research Data Effectively and Responsibly

Science, mathematics, and engineering education could be profoundly transformed by placing far greater emphasis on learning that is based on student interactions with complex data and systems (Birk, 1997; Lovett & Shah, 2007; McKagan et al., 2008; Pea, 2002; Vahey, Yarnall, Patton et al.,

2006). Classroom-ready environments could allow students to experiment with topics as diverse as galaxy formation, climate change, bridge designs, protein folding, and designer molecules. Students could discover important principles by changing the rules: making the gravitational potential an inverse square law, eliminating atmospheric ozone, using super-strong building materials, or creating impossible atoms.

The exploding computational power of computers has the potential to make this vision feasible, not just for a few advanced students, but for all students in secondary education and in introductory college STEM courses. Students can learn new ways of handling data, of reasoning from data and learning to generate their own hypotheses, and of the context of research endeavors (e.g., Blumenfeld et al., 2000; Edelson et al., 1999; Linn et al., 2004; Linn & Hsi, 2000; Pea et al., 1997; Polman, 2000; Reiser et al., 2001; Sandoval & Reiser, 2003). Research on teaching with sensor network data and with geospatial data both show promising results for learning (Borgman, Leazer, Gilliland-Swetland et al., 2004; Martin & Greenwood, 2006; Mayer, Smith, Borgman et al., 2002; Sandoval, 2005; Thadani, Cook, Millwood et al., 2006; Wallis, Milojevic, Borgman et al., 2006). There have been numerous experiments with introducing high-performance computing at the introductory science level (e.g., Dooley, Milfeld, Gulang et al., 2006; Sendlinger, 2008). The results have been stunning, but are not scalable because they almost invariably require programming and expert assistance.

A scalable design for computational models in education needs the following:

- **Easy experimentation.** Students must be able to quickly set up and run a model using an intuitive user interface. No knowledge of programming or system commands must be required.
- **High level of interactivity.** Models need to evolve quickly (typically in 20 to 40 seconds) and include smooth visualizations for providing the interactions and feedback that give users the ability to understand the

evolution of the system.

- **Classroom activities.** Models need to be embedded in educational activities that are consistent with research on learning and easy to deploy in typical classrooms. The materials should include assessments that provide feedback to teachers.

Research Questions:

1. How can STEM instruction incorporate authentic and realistic data from research, models, simulations, and other sources to improve lifelong science learning?
2. What forms of user interfaces and interoperable resources will allow students to easily experiment with resources such as simulation models and datasets established by and for experts?
3. What are the benefits for science learning of new data visualizations, immersive environments, modeling environments, sensor networks, and other technologies?
4. What are the general principles that can guide adaptation of computational resources to different education and learning settings?

3.3.3 Create Cyberlearning Initiatives Effectively and Responsibly

A major impact of cyberlearning on 21st century education will be through scientific advances coming from data mining of the vast explosion of learning data that will be emerging from uses of cyberlearning technologies. Such technologies will include interactive online courses and assessments, intelligent tutors, simulations, virtual labs, serious games, toys, virtual worlds, chat rooms, mobile phones and computers, wikis, and so on, used in formal and informal learning settings.

The deluge of learner data from cyberlearning technologies will be directly valuable to educators, parents, and students themselves, provided that data are properly handled and protected. (see discussions of Lifelong Learning

Chronicles in Ainsworth et al., 2005; see also Lynch, 2002) The data will also aid researchers in developing a more complete and accurate scientific understanding of what makes learning most productive and enjoyable. The sciences of academic and informal learning will be transformed by the vast and detailed data that will be available. With such data, researchers can tell, for instance, which math games or intelligent tutors really help students and which aren't worth the silicon on which they run. More important, the learner data deluge will drive new social and cognitive science and produce theories useful in educational systems design. More broadly, what the cyberinfrastructure is doing for other sciences,¹⁰ it can also do for the behavioral and social sciences of learning. However, unlike in most sciences, key ethical issues must be addressed on the use of human data, particularly appropriate access controls and privacy protections. While the resolution of these ethical issues goes beyond NSF's mandate, NSF should consider partnering with other organizations to take the lead in framing the questions and initiating a much-needed—even overdue—discussion.

3.3.4 Prepare Students for the Data Deluge

Scientists associate computational skills with learning programming languages or using certain tools. In this world of data deluge, we will need people who acquire a new way of “computational thinking,” to approach a new scientific problem (Wing, 2006). These algorithmic approaches to problem solving can be taught at a very early stage, starting even in kindergarten. Foundational work in advancing the learning of computational thinking has been provided by prior NSF-funded works by Seymour Papert, Andrea diSessa, Uri Wilensky, Mitchel Resnick, Yasmin Kafai, Fred Martin, and Michael Eisenberg, among others. Publishing, authoring, and curating large amounts of data require new skills, those of “data scientists,” the instrument builders of the 21st century. NSF is recognizing the need for developing these skills, and the recent Cyber-enabled Discovery and Innovation (CDI) and

DataNet solicitations are targeting such activities. How to productively identify and exploit patterns represented in large amounts of data is a yet-unsolved question whose answers are in substantial flux. Some of the world's largest companies (Google, Yahoo, Microsoft, Amazon, eBay) are struggling with these issues as we write. Individually customizable portals and custom tagging are emerging as promising directions. Harnessing them for use within education will become a core challenge.

Teenagers have adapted to navigating the Internet with a natural ease, and huge online communities (e.g., Facebook, Myspace) have created tens of petabytes of digital data in a very short time. This millennial generation naturally immerses itself in massive multiplayer online role-playing games (e.g., Everquest, Halo, World of Warcraft) as well as virtual worlds (such as Second Life), which constitute data-rich landscapes. The educational community should watch these emerging trends and ideas and be ready to quickly adopt them for educational use (for examples, see Barab, Sadler, Heiselt et al., 2007; Nelson & Ketelhut, 2007).

Research Questions:

1. What simple steps can be taken to introduce computational/algorithmic thinking for a networked world into the K–12 and higher educational process?
2. How could data navigation and management skills be taught at a much broader level? What tools, virtual worlds, interfaces, and games can be used to introduce students to these concepts?
3. How can inexpensive sensors be used in innovative ways to introduce students to the concepts of hands-on experiments, data sharing, and the interpretation of noisy data?

¹⁰ “Scientists in many disciplines have begun revolutionizing their fields by using computers, digital data, and networks to replace and extend their traditional efforts” (Atkins et al., 2003, p. 9).

3.4 Target New Audiences With Cyberlearning Innovations

Experience with educational resources placed on the Internet reveals that they are used in unanticipated ways by unanticipated audiences. The scope of NSF cyberlearning initiatives should extend across the entire range of learning venues, both formal and informal, and to all learners. NSF-funded resources should be designed so that they can be easily multipurposed to new applications that serve audiences originally unanticipated by the developers. For example, open educational resources today are commonly provided with licenses (from Creative Commons, for example) that allow adaptation, mixing, mashups, and so on. Similarly, software should be modular, with components that are open, available, and as user friendly as possible for all users. Issues of universal accessibility as well as multilanguage accessibility will need to be addressed.

We also need a stronger emphasis on the importance of reaching out to users in the codesign and construction of tools and archives from the beginnings of their inceptions, not as afterthoughts. It is important to recognize that multipurposing must go beyond merely adapting the content to providing appropriate training and support targeted to educators and learners in very diverse settings. As an example, we note that the indoor-outdoor integration of mobile computing for education has introduced two important features into the learning environment— context awareness and content adaptivity (Pea & Maldonado, 2006). Context awareness means that the pedagogical flow and content provided to the learning environment should be aware of where learners are (e.g., geographic location). Content adaptivity means that the different learning contents should be adaptable to the learners' settings, so that time- and place-appropriate activity supports, information, and technical capabilities are made available. These features could play important new roles in designing mobile applications that

support the inquiry processes and socially mediated knowledge building associated with learning science by doing science, as in capturing and analyzing data from environmental sensors.

As we consider the opportunities of vastly extended informal learning opportunities, there are also opportunities for collaborations with other organizations—for example, science and natural history museums or the Public Broadcasting Service—that have interests and expertise in this area.

Research Questions:

1. What are the general principles that can guide adaptation of materials to different learning and educational settings?
2. What tools can be used to facilitate this adaptation?
3. What cyberlearning design principles are emerging from current work, and how can they guide developers so that materials meet the needs of diverse audiences and work in diverse settings, including home, school, and informal learning?

3.5 Address Cyberlearning Problems at Appropriate Scales

Cyberlearning offers new opportunities for scaling innovations as students and teachers form social networks, join professional organizations, or participate in educational activities. Designers can target new, emerging audiences or social networks like high school math teachers who are already using the Math Forum,¹¹ members of the International Society of the Learning Sciences, or teachers who use the Whyville, a multiplayer game, as part of their curriculum.¹² These social networks form natural segments of the audience that can provide detailed feedback to designers.

Innovations implemented with networked or cellular technology can increase the seamless nature of learning (across home, school, museum, or playground) to attract and support users. The

11 See Math Forum: <http://mathforum.org>.

12 See Whyville: <http://www.whyville.net/smmk/nice>.

multiple scaling opportunities and information sources motivate new approaches to design. Rapid prototyping, testing, and revision of innovations enable design communities to respond to varied user needs. The opportunity to create community knowledge resources that depend on users to develop them raises intriguing research questions. The boundary between design and implementation has blurred, creating exciting new opportunities and research questions.

Researchers might, as in the case of Galaxy Zoo (see GalaxyZoo inset), release a cyberlearning tool one morning and reach 100,000 users by nightfall. At the same time, researchers might choose to work initially with a group of 20 users, each with

GalaxyZoo.org

In July 2007, a group of astronomers created a mashup of galaxy images from the Sloan Digital Sky Survey (the Cosmic Genome Project), the world's largest digital map of the universe. The public was asked to perform a simple visual classification of about a million galaxies. The response was overwhelming: more than 100,000 people participated and created 40 million classifications. The results were on par with a similar, but much smaller scale, effort made by professional astronomers. The level of enthusiasm resulted in thousands of blogs by video gaming communities, and the participants were thrilled by being able to help in doing real, meaningful science. As a punch line, in December 2007, a Dutch physics teacher noticed an irregularity near one of the galaxies and published a blog about the object (Yanni's Voorwerp). Her discovery produced a truly unique, original discovery, and the object has since been observed by several of the world's largest telescopes and space observatories (Lintott, 2008).

ties to at least 20 other users through their social network. Over time, the researchers might grow their study to include these secondary participants, scaling the study in relation to emergent flows within the network.

These opportunities require developers to “build a little and test a lot.” Networks and the communities of users they support are dynamic systems—users can react to, iterate upon, and extend the experiences and products that are available. Developers can aggregate experiences where users themselves have had a hand in developing the innovation (Von Hippel, 2005). Balancing local goals and insights emerging from multiple users offers a new, exciting challenge for education. Developers can design for a strategy of agility. The ideas that software should be built for users or last for many years are cultural assumptions, not required by the software itself. Instead, designers can create materials that lend themselves to effective customizations and support local experimentation and revision.

Research Questions:

1. How can scaling opportunities build on the open-platform opportunities?
2. How does scaling work in a networked, distributed community of learners? Who is marginalized, who is empowered?
3. How can industry experiences contribute to scaling of cyberlearning resources?
4. What are promising research methodologies for studying scaling opportunities?

3.6 Reexamine What It Means to “Know” STEM Disciplines With Cyberlearning Technologies

NSF needs to encourage evidence-based rethinking of what K–20 STEM cyber-enabled learners need to know and be able to do. We recommend that NSF convene interdisciplinary workshops to survey the state of the art for reconceptualizing STEM domain knowledge, curriculum resources, activity structures, and assessments when cyber-infrastructure technologies are integral to STEM learning and teaching. Planning should work toward funding (Kaput & Schorr, 2002) foundational studies that restructure STEM knowledge domains for learning

effectively using the interactive, representational, and data-mining capabilities of cyber-infrastructure.

Extensive research in the cognitive sciences has indicated that deep conceptual analysis of the knowledge structure of a STEM domain is important for revealing what is required to achieve adaptive and flexible problem solving within that domain (Bransford et al., 2000) (e.g., work on qualitative physics about thermodynamics) (Forbus, 1997; Linn & Hsi, 2000). New fundamental research questions arise as this kind of analysis is extended for understanding how STEM learning and scientific practices change when there is change in the interactive properties of the medium in which knowledge is represented, constructed, and communicated (e.g., DiSessa, 2000; Duschl et al., 2007; Kaput, 1992; Kaput et al., 2007; Papert, 1980; Wilensky & Reisman, 2006). As the late mathematician James Kaput argued for mathematics learning revised with interactive technologies, representational infrastructure changes everything and can open up new opportunities to learn, democratizing access to higher levels of mathematics, as in the “mathematics of change and variation” strand from elementary school through the first year of university (see SimCalc inset) (Kaput & Schorr, 2002).

Humans reason differently in STEM domains—and learn differently—when the knowledge representational systems for expressing concepts and their relationships are embodied in interactive computing systems, rather than historically dominant text-based or static graphical media. For example, scientists working in laboratories conduct inquiries *inside* computer models of weather systems, fluid flows, or disease propagation, and reason *through* the representations with which they interact to make inferences about the world that they represent. For many inquiries in complex adaptive systems—such as the biosphere, ecosystems, marketplaces, chemical reactions, or materials phase changes—agent-based computer modeling techniques are used to investigate emergent phenomena from dynamic networks of

many agents (which may represent molecules, species, cells, individuals, or companies) acting in parallel and in reaction to what other agents are doing [e.g., Santa Fe Institute-inspired work and NetLogo models (Wilensky & Reisman, 2006)]. In yet other common scientific practices, colorful and dynamic information visualizations are created from extremely large datasets with terabytes of data to investigate patterns of change over space and time in climate studies,

SimCalc

SimCalc is an important example of how new properties of technology enable a restructuring of fundamental mathematics content, enhancing student learning. Beginning with a 1993 NSF grant, the SimCalc Project has pursued a mission of “democratizing access to the mathematics of change and variation”—which translates to introducing students in grades 6–12 to the powerful ideas underlying calculus while simultaneously enriching the mathematics already covered at those grade levels. SimCalc developers Jim Kaput, Jeremy Roschelle, and Stephen Hegedus viewed technology as valuable for its new representational and interactive capabilities: SimCalc signature MathWorlds software gives students the ability to sketch graphs and see resulting motions. In connection with paper curriculum materials, students learn to connect key concepts, such as rate, across algebraic expressions, graphs, tables, and narrative stories. SimCalc also exemplifies a determined effort to scale up from basic research findings to statewide experiments. Early basic research within the SimCalc Project began with very small classrooms, design methodologies, expensive technologies, researchers acting as teachers, and other unrealistic elements. In subsequent projects, the team gradually moved to greater scalability and realism. Research transitioned from a few students, to a few teachers, to a few schools, and eventually to large numbers of teachers across the State of Texas. Research methodologies also transitioned from design experiments to randomized

experiments with carefully designed controls. The team reduced technology costs by moving from high-end desktop computers to more affordable and commonplace laptops and handhelds, including TI graphing calculators. Perhaps most important, the team continually refined its materials and approaches until they could be implemented successfully by large numbers of ordinary teachers in ordinary schools.

With support of a culminating \$6 million NSF grant, the team collected data from classrooms of 95 seventh grade and 58 eighth grade teachers. The results showed greater learning gains for students in classrooms implementing SimCalc, especially for more advanced mathematics concepts. The results were also robust in varied settings with diverse teachers and students. Across boys and girls, white and Hispanic populations, impoverished and middle-class schools, rural and suburban regions, and teachers with many different attitudes, beliefs, and levels of knowledge, students learned more when their teachers implemented SimCalc. Continuing research at the James J. Kaput Center is seeking to expand SimCalc learning gains into high school and to deepen learning using an additional advance in technology: wireless networking. New SimCalc designs aim to enhance student participation in SimCalc classrooms by allowing the teacher to easily distribute, collect, display, and aggregate student work over a wireless network. New forms of social activity assign each student a unique mathematical role in a classroom activity while pulling together the contributions of many students to simulate and visualize more complex mathematical objects, such as a family of functions.

epidemiological patterns of disease flow, severe weather fronts, and changing patterns of species distribution associated with global warming.

Research Questions:

1. How can domain knowledge best be restructured for learning and teaching through cyberinfrastructure technology?
2. What STEM learning domains and developmental levels are most in need of revisioning using cyberinfrastructure to open up accessibility of STEM understanding to all learners?
3. What are the best available forms of evidence to support such arguments of priority?
4. How can interdisciplinary teams most productively pursue alternative conceptualizations and designs for STEM domain cyberlearning? What rapid prototyping technologies are needed for exploring and empirically assessing such alternatives?

3.7 Take Responsibility for Sustaining NSF-Supported Cyberlearning Innovations

After too many experiences with educational innovations emerging from NSF becoming unusable after a few years, when the original developers have lost funding or moved on to other projects, teachers have become reluctant to implement these innovations. NSF should develop a process for identifying which projects should be sustained and put processes and mechanisms into place for sustaining innovations deemed deserving. Practical sustainability requires not only making materials available to all, but also paying attention to continued training and development, promotion, and business models. Most often, the original researchers are not the appropriate people to undertake these phases of a product life cycle. NSF should implement effective partnership development and hand off programs so that valuable innovations remain in use and can be built upon.

For any endeavor of this scale to succeed beyond the initial stage(s), it is crucial to formulate and solidify cross-sector initiatives and formal partnerships with related Government agencies,

private industry, charitable foundations, the higher education sector, and key nongovernmental organizations. This is certainly not a new concept, but addressing sustainability as an up-front, foundational element is an important initial step that is frequently overlooked. Ideas and concepts that might not have worked in the recent past or that were dismissed for valid reasons years ago should likely be reconsidered, as the timing and the circumstances might now be ideal for them to succeed.

Several strategies should be explored by NSF for sustainability:

- **Fund incubations.** NSF should investigate incubation activities to fuel innovation in cyberlearning. One model is a derivation of the thriving IdeaLab¹³ concept (with central hub/exchange and core services—but freedom for innovators) that could be offered to higher education faculty during the summer. Imagine a number of universities with appropriate facilities making their campuses open by hosting multidisciplinary teams focused on rapid prototyping of cyberlearning tools, thus leveraging the availability of information and communication technology (ICT) resources to develop proofs of concept. These “technical swarms” around a creative core could produce viable scenarios and feasible technologies that would attract the attention of invited venture capitalists and research teams.

- **Establish competitions and challenges.** In conjunction with select partners (foundations or commercial entities or both), initiate several high-profile grand challenge competitions. These could be multiple small events or a limited set of more significant undertakings. The best recent example is the X-Prize Challenge,¹⁴ in which an initial single concept has morphed into a broader set of

opportunities, resulting in true, feasible solutions and functioning businesses. A more closely related project is the Digital Media and Learning Competition¹⁵ sponsored by the MacArthur Foundation and administered by the Humanities, Arts, Science and Technology Advanced Collaboratory.

- **Motivate participation across the private sector.** Open up requests for proposals or agree to cofund/cost-share the development of cyberlearning technologies with the private sector to stimulate innovation and encourage new businesses and business models. NSF could solicit proposals from private industry and high-tech industry firms to build out cyberlearning platforms or modular technologies to ensure that the ecosystem is cooperatively working around established community protocols. Consider partnerships with the higher education sector contacts at Apple, 3Com, EMC, HP, Intel, Microsoft, and others, who would be likely to invest in developing or partnering on the buildout of cyberlearning (test) environments if it would lead to additional business and services in the future.

There may be cyberlearning innovations that become so central and important that NSF (or the Government more broadly) should support them directly on an ongoing basis, as happened with CSNet and NSFNet¹⁶ before the Internet opened to commercialization.

Research Questions:

1. What should the life cycle of an educational resource be, and what kinds of professionals and organizations are needed to support the different phases of this life cycle?
2. What are viable sustainability models for NSF-supported innovations?

What are the characteristics of an organization that can actually sustain the quality of these resources?

¹³ <http://en.wikipedia.org/wiki/Idealab> and <http://www.idealab.com/>

¹⁴ <http://www.xprize.org/>

¹⁵ <http://www.dmlcompetition.net/>

¹⁶ <http://www.nsf.gov/about/history/nsf0050/internet/launch.htm>

3.8 Incorporate Cyberlearning Into K–12 Education

Infusing cyberlearning into precollege education starts with partnerships of K–12 educators, school leaders, curriculum designers, technologists, informal educators, and researchers who work together to transform educational programs and make education more seamless (Pea et al., 2003). This approach requires attention to the whole educational system, including assessment, standards, curriculum, school leadership, school finance, and professional development. A vast array of reports deplores the sorry state of education today and calls for innovative solutions. Small, innovative programs offer considerable promise to respond to this situation but need additional investigation. (See *Science's* "Education Forum" articles from the previous 2 years.)

Until recently, the biggest obstacle to cyberlearning was access to technology for learners. Today's students are connected¹⁷—although schools often lack up-to-date or powerful technologies as well as funding models to maintain their resources. (See *U.S. Digest of Education Statistics, 2007*.)¹⁸ California data for 2007¹⁹ indicate 4.6 students per Internet-connected computer, with nearly 50 percent of computers 4 years or older.) Internationally, access to cell phones, PDAs, and \$150–\$300 laptops is growing from One Laptop per Child and Intel Classmate, among others. They provide opportunities for connecting out-of-school and in-school learning.

Currently, the challenge is to determine the most effective ways to use cyberlearning and to investigate promising directions that take advantage of its potential. Already, students use technology for social networking, working, gaming, and researching pop culture—but far less for educational activities. Making these uses of technology more seamless has tremendous potential but will require focused attention to the research and implementation challenges that must be addressed to make this vision a reality.

In incorporating cyberlearning into education, it is important to consider the role of assessment, curricular standards, professional development, and school finances. Since teachers and administrators are ultimately responsible for classroom learning, efforts are needed to create professional development programs that support decisionmaking about the use of cyberlearning tools in the classroom and how to best leverage technologically enhanced learning at home and in communities. These programs need to enable teachers and administrators to understand the benefit of cyberlearning for students and teachers and to design effective ways to implement cyberlearning in their schools and the broader learning ecosystem outside schools.

Opportunities for gathering data on student and teacher activities to make education more effective need investigation, as we have earlier highlighted. Embedded assessments give learners and their teachers a far richer source of evidence for the impact of materials than has ever been possible. For example, teachers can access information about student progress while class is going on, as students work in small groups. Teachers could look at a random sample of students' experiments, read the notes students write, or get a summary of the progress of each small group. What is the best way to make this information available to teachers? Do teachers want to personalize the reports they get during instruction? Do they want to work with a more experienced coach to interpret the information? Can automated interpretive guides be developed to support their reasoning about educational data? In a similar vein, after the unit has been taught, teachers could take advantage of the well-documented powers of formative assessment (Black & Wiliam, 1998) to get summaries of student reactions to each segment of instruction and use this information to revise the instruction before they teach the unit again. What is the right professional development program to support such activity? How can this information transform education?

17 http://www.pewinternet.org/PPF/r/230/report_display.asp and http://www.pewinternet.org/PPF/r/162/report_display.asp

18 http://nces.ed.gov/programs/digest/d07/ch_7.asp

19 <http://www1.edtechprofile.org/graphs/report-1216568534.pdf>

Since teachers, and the administration to which they are responsible, are in charge of what goes on in the classroom, effectively bridging to the classroom requires developing teachers (and administrators) who are comfortable with the use of cyberlearning tools in the classroom, understand their benefit to student learning and teaching, and are committed to implementing them in the classroom.

Research Questions:

1. How can the potential of cyberlearning be communicated broadly to stimulate widespread experimentation with new approaches to education?
2. What forms of cyberlearning are most effective for STEM education, given limited resources?
3. How can promising materials be widely disseminated and sustained for an educationally appropriate time frame?
4. What are effective ways to transform professional development of pre-service and in-service classroom teachers in STEM disciplines with cyberlearning resources and sustain promising approaches?
5. How do we support changes in the educational system to provide effective materials, meaningful guidance on pedagogical approaches for implementing cyberlearning, assessment, classroom management, and leadership in the cyber-enabled classroom?

A 21st Century Agenda for the National Science Foundation



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4. Opportunities for Action

The above strategies, while not a comprehensive set of possibilities, were chosen because they represent a core set of activities that NSF should pursue to make cyberlearning a reality. Some require *community workshops* to develop consensus; others are sufficiently well developed that *programmatic initiatives* can be launched soon. Here we articulate seven important opportunities for action that we feel have the greatest short-term payoff and long-term promise among the many that NSF might pursue: (1) advance seamless cyberlearning across formal and informal settings, (2) seize the opportunity for remote and virtual laboratories, (3) investigate virtual worlds and mixed-reality environments, (4) institute programs and policies to promote open educational resources, (5) harness the scientific-data deluge, (6) harness the learning-data deluge, and (7) recognize cyberlearning as a pervasive NSF-wide strategy.

4.1 Advance Seamless Cyberlearning

Education tends to be intentionally designed and provided either inside formal institutions like schools or as informal education inside science museums or afterschool centers. This can and should change, given the enormous changes in the digital resources, Web browsers, and other ICT platforms now available and increasingly used for learning outside formal designs. Advancing seamless cyberlearning across formal and informal settings is a large-scale opportunity where NSF investment could make a tremendous difference. Learners are in motion. But supports for their extended learning and education are not—to the detriment of the Nation and greater learning for all. Learning support systems can and will be organized along very different schemes than they are today, given the computational services made possible with cyberinfrastructure advances.

Seamless cyberlearning is learning supported by cyberinfrastructure so that it can be pursued

productively either through learner intent, driven by interests or demands in the moment and regardless of location, or through intentionally designed educational activities, which learners can take advantage of as needed or when the situation requires (e.g., during schooling). This characterization indicates that seamless cyberlearning is about far more than just access to online courses anytime, anywhere—as important as these developments have been recently (Atkins et al., 2007). But what else does seamless cyberlearning entail? For example, youth today are extensively exploiting computing and mobile telephony outside of school to pursue their interest-driven learning through social networks. They use social network platforms like Facebook, MySpace, YouTube, blog sites, search engines, and instant messaging, not only for socializing, but to advance their learning and that of their peers about topics of personal consequence, such as hobbies, music, sports, games, fan culture, civic engagement, health, and nutrition, as described in the 2007 MacArthur Series on Digital Media and Learning.²⁰ Such interest-driven learning tends to be pursued outside school and often remains unconnected to school. At the same time, we know how vital the funds of knowledge and interests that learners develop in their everyday lives can be to promoting an integrated learning with formal education, in STEM domains, and for other life competencies (A New Day for Learning, 2007; Bransford et al., 2006). In fact, Estabrook, Witt, and Ramie (2007, p. iii) found that more youth as well as adults “turn to the internet...than any other source of information and support, including experts and family members” for help with many common problems.

Yet today learners for the most part have to exert their own efforts to coordinate the repertoires of knowledge and practices that they have developed through their experiences across many different settings, from classrooms to home, community to workplace. It is becoming increasingly evident that solving the problems

²⁰ (Bennett, 2007; Buckingham, 2007; Everett, 2007; McPherson, 2007; Metzger & Flanagan, 2007; Salen, 2007).

affiliated with education and learning will require attending to design of the whole spectrum of experiences in which learning occurs, not only schooling and other formal educational institutions (Bransford et al., 2006). Creating environments for seamless learning requires vital cyberlearning infrastructure research and development (Ainsworth et al., 2005). Cole (1996) differentiates context as “that which surrounds us” and “that which weaves together.” The latter definition makes clear how important cyberlearning infrastructure is likely to become, as it provides the technical substrate for weaving together in new designs the disparate learning and educational intentions and resources to make seamless cyberlearning a reality.

Seamless cyberlearning presents numerous “grand challenge problems” for research (Pea, 2007). Examples include (1) providing real-time access to developmentally relevant cyberinfrastructure learning support that will guide any learner toward meeting any learning standard, configuring requisite learning resources and human help from peers or mentors with verifiable reputations to help the learner attain such competencies in a certifiable manner; (2) creating “interest profiles” by inferring learners’ interests from data-mining digital information on what they read, talk about, and attend to (with appropriate privacy safeguards), which can then be used for compiling engaging content and scenarios for their pursuit of enhanced skills and competencies using cyberinfrastructure; (3) providing Lifelong Digital Learning Portfolios for cyberinfrastructure management of all information media developed by a learner over a lifetime, in a manner usefully indexed for the learner’s reflective learning and certification purposes.

While examples exist both in the United States and abroad of seamless cyberlearning starting to appear (e.g., Pea, 2006; Rogers, Price, Randell et al., 2005; Sharples, Taylor & Vavoula, 2007; Van’t Hooft & Swan, 2007), without concerted and focused efforts to galvanize new developments using cyberinfrastructure, large opportunities for connecting learning experiences across settings

are being lost. Achieving seamless cyberlearning will require advancing all of the strategies for building cyberlearning initiatives articulated in section 3 above, in particular, instilling a platform perspective, targeting new learning audiences with agile multipurposing of content, and instrumenting cyberlearning initiatives to capture metrics of learning experiences to improve them.

We recommend that NSF develop a program that will advance seamless cyberlearning across formal and informal settings by galvanizing public-private partnerships and creating a new interdisciplinary program focused on establishing seamless cyberlearning infrastructure and supports.

Research Questions:

1. How can cyberlearning infrastructure be used to mediate personalized learning across all the contexts in which it happens?
2. How can the “right” resources, from digital assets to human peers and mentors, be provided in any context to support learning needs in the moments in which they arise?
3. What different needs exist for different age populations and STEM learning domains?
4. What scaffolding systems are necessary to support learning in these distributed learning environments (Pea, 2004)?
5. How should theories of learning and instructional design be expanded to encompass learning across the boundaries of all the settings in which people learn?
6. What forms of digital portfolios will be necessary to manifest evidence demonstrating learning activities and performances?

4.2 Seize the Opportunity for Remote and Virtual Laboratories to Enhance STEM Education

Laboratories—both those focused on observation and experimentation and those focused on

design, fabrication, and testing—are an essential part of the teaching and learning experience for many branches of science and engineering, from grade school through postdoctoral work. Ideally, laboratories provide a window on science in the making, showcase the ambiguity of empirical work, develop practical skills, and foster teamwork abilities (Singer, Hilton & Schweingruber, 2005). Achieving these goals has proven problematic. Laboratories are expensive to maintain, they require low student-faculty ratios, and they depend on both talented teachers and well-designed activity sequences. They raise safety and ethical issues around toxic substances and biological phenomena. Even when physical labs are available, they often are scarce resources, with student lab time tightly rationed and faculty guidance limited.

NSF has the opportunity to improve the impact of laboratories as well as reduce the cost of providing laboratory experiences, by promoting infrastructure for virtual laboratories and remote laboratories. Virtual laboratories include interactive simulations of laboratory equipment and experiments as well as interactive models or simulations of scientific phenomena that are too small, fast, or complex to explore in typical classrooms. These resources are completely scalable and can be embedded in powerful curriculum materials.

Remote laboratories allow students to access physical laboratory equipment via the Internet. Students at many different locations can share the use of physical equipment, as in the MIT iLabs project, which has microelectronics test equipment and other instruments on the Web. MIT is collaborating with universities in Nigeria, Uganda, Sweden, China, and Australia around its use (See inset on Inverted Pendulum). In addition, some labs are giving students access to unique, world-class observational resources such as major telescopes or electron microscopes. These programs offer promise but have scaling limitations.

We recommend that NSF mount a program to stimulate development of remote and virtual

laboratories and to research effective ways to deliver this type of instruction. Many studies reveal the weaknesses of both hands-on and virtual laboratories (Singer et al., 2005). We recommend funding centers to identify effective ways to provide laboratory experiences given the power of cyberlearning technologies.

Creating effective cyber-enabled laboratory experiences requires an investment in curriculum design, experimental research, and infrastructure. Creating effective ways to use these new resources requires trial and refinement, ideally conducted in the range of contexts where they will be used. Even with a promising, tested starting point, faculty need time to reimagine and redesign their courses and determine the impact of the innovations.

For virtual labs, we need focused attention on pedagogy, scale, and interoperability. Much excellent work (some of it funded by NSF) has been done to build software chemistry sets, biology labs, and basic experimental physics labs. Research also suggests instructional conditions under which these resources succeed or fail (Clancy, Titterton, Ryan et al., 2003). We need to think about how to make materials extensive and customizable. We need to consider the role of standards or other types of interoperability frameworks, something that might be done in the context of the open cyberlearning platform initiative described above.

Schools and universities need to create and maintain the infrastructure investment to facilitate the deployment and use of remote labs. Faculty fear that they may be forced to extensively redesign courses every year or two because of the lab equipment available to their students. We need to explore financial and support arrangements for sharing experimental and fabrication equipment worldwide. We also need resource-sharing policies, and mechanisms for scheduling, and where necessary, rationing the use of such equipment. For sustainability, we may need recharge mechanisms or some other system of allocating equipment time among remote users.

The University of Queensland Inverted Pendulum Remote Laboratory

The University of Queensland (UQ) was struggling to provide adequate access for students required to take a control theory course in its undergraduate program. Physical space limited class size to 60 students. Additional laboratory space was unavailable. Course content was challenging and uninspiring. Take the classic inverted pendulum control experiment. The student attempts to balance a pendulum with the weighted arm pointing upright toward the ceiling rather than hanging toward the floor. Students first write a Simulink model for the experiment and then write a MatLab program to control the motor that swings the pendulum, giving feedback from two sensors in the pendulum arm. Students work in teams of four to iteratively attempt to balance the pendulum via their MatLab application. Prior to the introduction of the iLabs pendulum implementation, 5 percent of the teams balanced the pendulum by the end of the 5-week experiment, while spending 50 contact hours on the task.

The iLabs inverted pendulum made the experiment accessible beyond lab hours. The iLabs software interface presented the data graphically and via a mixed-media video cam overlaid with a data-driven animation of the pendulum arm. This let students see the results of one experimental run directly compared with another, thus visually showing the impact that their code revisions caused. But the learning story is more compelling still. Students ran 30 to 40 experiments per team in the 5-week period prior to iLabs. With the remote lab, students ran 3,210 experiments, or on average 39.1 experiments per student. Contact hours decreased to 4 per week in the iLabs implementation from 10 hours per week previously, and the success rate for students balancing the pendulum went from 5 percent to 69.5 percent. Class size was increased from 60 students to 84 students, and student ratings of the course rose from 4.19 to 4.78 on a 5-point scale.

Finally, continued investment and emphasis is needed to ensure that scientific and engineering research programs that rely on cyberinfrastructure support perform the often modest incremental work to make their data available for analysis and reuse in instructional settings.

4.3 Investigate Virtual Worlds and Mixed-Reality Environments

Students today spend large amounts of time interacting with content and communities that are located in digital—or virtual—environments. These environments are both motivating and engaging and have many of the qualities defining the innovative potential of cyberlearning: they are *networked*, which allows for exchange between a variety of learners who do not have to be in the same physical space; they are *customizable*, in that they can be tailored to fit the needs and interests of learners on demand; and they support *computationally rich* models and simulations, which offer learners access to rich STEM content. As a result, online digital environments hold promise for cyberlearning in both the short and long term.

These digital environments sometimes take the form of virtual worlds. In these worlds learners can create a digital character, or avatar, to represent themselves, which they use to move around inside a virtually rendered world space shared with thousands of other avatars. They can socialize with others; build objects and share them; customize parts of the world; and hold lectures, do experiments, or share data. Individuals of many different ages are currently members of virtual worlds like Second Life, Whyville, There, and Activeworlds.

While virtual worlds occupy purely digital space, another kind of digital environment has similar promise: mixed-reality environments that combine digital content and real-world spaces. Interaction goes beyond a simple face-to-screen exchange, as in the case of virtual worlds, instead incorporating surrounding spaces and objects. To picture this, imagine a group of students in a lab interacting with a physics simulation being projected on the floor below them. Through the use of a wireless controller and motion sensors, the students are physically immersed in the simulation. They can *hear* the sound of a spring picking up speed, *see* projected bodies moving across the floor, *feel* the controller in their own

hands, and integrate how the projected image moves in accordance with their own body movements to construct a robust conceptual model of the system.

The benefits of utilizing mixed-reality environments and virtual environments for learning are many. In the case of virtual worlds, time and distance become irrelevant, allowing cyberlearning to occur any time, any place. The benefit to data collection practices cannot be overstated. Visualization is enhanced dramatically, which creates opportunities for new modes of interaction, new audiences, and new models of assessment. With mixed-reality environments emerging, sensing technologies can be used to diagnose a learner's interests and patterns of activity (i.e., what they search for, read, listen to, talk about, and attend to), allowing the system to learn about the kinds of choices students are apt to make. Consider the previous example. Within the physics simulation, projected mass and spring models move across the floor as dynamic sounds articulate the velocity and acceleration of the moving particles. Relational models allow the system to identify that the student would benefit from increased physical activity in the space to drive the system in ways that reveal important relationships that otherwise remain hidden. Models of a student's past actions reveal a hesitancy to explore movement but a heightened sensitivity to auditory feedback. Faced with these data, the system encourages the student by triggering an *adaptation*: small physical movements in the space give rise to amplified changes in the sound that encourage further embodied exploration between these attributes of the underlying system. The student is drawn out through the sonic experience in the environment, and correct intuitive understanding of the simulation is reinforced through actual experimentation.

The ability for mixed-reality environments and virtual worlds to provide real-time access for learners—whatever their developmental capabilities or interests—means such platforms can guide students toward meeting any learning standard. In addition, these spaces allow for a

kind of collaboration and exchange that have been difficult to achieve in traditional learning environments.

NSF should begin investment in leveraging the use of virtual world and mixed-reality environments for STEM learning. This includes developing an infrastructure for assessment and support and requires connection to larger concerns around openness, virtual laboratories, and the data deluge.

4.4 Institute Programs and Policies to Promote Open Educational Resources

In education, as in so many areas of human activity, the burgeoning of the World Wide Web is the most significant cyberinfrastructure phenomenon to emerge in the past 50 years, and the one with perhaps the greatest transformative potential for education. In the 1990s, educators regarded the Web primarily as a low-cost distribution mechanism: author-educators (including NSF grantees) would create materials and make them available on Web sites for students and teachers to access.

Increasingly, however, the Web is being recognized as an enabler for collaborative creation of significant information resources that aggregate contributions from hundreds or thousands of individuals. Wikipedia is the most famous example of the collective intelligence of crowds. Collaborative creation is especially appropriate for educational materials, including text, video, simulations, games, and other content, because the effectiveness of educational materials often hinges on the ability to adapt them to fit the needs of particular cultures, school systems, and classrooms—even individual teachers and learners. In education, therefore, resources on the Web are especially valuable if they are *open educational resources* (Smith & Casserly, 2006).

Open educational resources (OER) are teaching, learning, and research resources that reside in the public domain or have been released under an intellectual property license that permits their

free use or customization by others. Open content includes video, multimedia, cognitive tutoring courses, open textbooks, journals, books, data, laboratories, music, library collections, lesson plans, simulations, games, virtual worlds, and so on. Other OER include freely usable and reusable tools to support open content, including open-source content and learning management systems, search engines, communication systems, and intellectual property licenses. Major institutions such as the BBC, U.S. public television stations, and Harvard University are unlocking their resources from behind passwords, intranets, and archives and figuring out ways of making them available to everyone, everywhere. But it is the freedom to share, improve through rapid feedback loops from users and other experts, reprint, translate, combine, or adapt them that makes OER educationally different from resources that can merely be read online at no cost. The importance of openness is now being recognized worldwide, both in developed and developing nations (Atkins et al., 2007; Wilensky & Reisman, 2006).

There are noteworthy examples of OER in many STEM-related areas. Three examples of special interest are (1) the OpenCourseWare activities described earlier, which have spread across the world and receive multimillion visits monthly; (2) open textbooks to address the high price of texts, the lack of quality in many of them, and their scarcity in many developing nations; and (3) open full courses in mathematics, engineering, and science. The open textbook movement is picking up momentum at the secondary school and community college levels, especially in mathematics and science. The power of an open textbook is that it provides the opportunity for users to modify, adapt, and extend it to adapt to new knowledge developments in its field and to improve its usefulness in classrooms and for students in different cultures, at different levels of prior knowledge, and with different languages. Open textbooks can also be augmented with video, simulations, and assessments and may be modified to provide feedback loops for students to relearn material that the assessments indicate they have not mastered. In effect, the textbooks

can facilitate individual tutoring, sometimes called personalization.

Some open full courses already have the capacity to provide such personalization. In particular, the Carnegie Mellon cognitive tutor courses have this capacity. In a recent experiment, a randomized group of Carnegie Mellon students used the cognitive tutor statistics course and, given only half the time (a 7-week semester), were more successful on the final examination than students who had taken the normal full-semester lecture course (Lovett, Meyer & Thille, in press). The power of technology to provide personalization will become greater and greater as we improve the quality of the instructional aspect of the Web-based courses. Ensuring the quality of the content requires considerable one-time costs as it is built into modular courses and from then on some modest updating costs. However, the net costs over even a short period and the guarantee of high-quality content for our students suggests that we can imagine a substantial increase in access and learning.

In open access of research results and scholarly journals and other publications, there are extensive and complex developments both in the United States and elsewhere. A move toward open access is happening rapidly both at the level of funding agencies (notably the recent requirement for the deposit of articles describing research funded by the National Institutes of Health [NIH] within a year of publication, so that these articles are available for public access) and at the level of individual institutions of higher education, such as Harvard. In addition there are literally hundreds of open academic journals. There are also movements to encourage the sharing and reuse of data (although this is subject to constraints such as human subject regulations, of course). All these developments will help to contribute to the effectiveness of cyberlearning initiatives. We would certainly welcome, for example, a NSF policy on articles reporting research results that was at least as strong in encouraging open access as that adopted by NIH (and would also urge that some thought be given to consistency of policy across Government agencies).

With regard to materials developed with NSF funding that are primarily educational in nature (rather than reports of research results or research data)—and recognizing that this is a slippery distinction—we believe that an NSF-wide policy that encourages principal investigators to make their materials open and to be concerned about their sustainability is essential.

1. NSF should require clear intellectual property and sustainability plans as part of grant proposals for educational materials it supports. The default expectation around intellectual property is that the materials should be released on the Web as open educational resources under a license provided by Creative Commons, where appropriate (perhaps with attribution only), at some identified point within the term of the grant. This will facilitate machine searching and processing of the material and also help with reuse and recombination of materials. As part of the evaluation of proposals, grant reviewers should give careful attention to these plans, and also to any arguments advanced for more restrictive conditions on NSF-funded educational materials.

One challenge of open educational resources is that of creating sustaining funding models so that materials remain available and improve over the long term. For some OER materials there may be long-term public or university funding. Other materials might be maintained by subsequent reusers. The cost of storing vast quantities of content drops dramatically every year, and organizations such as the Internet Archives make storage and bandwidth free. There could be commercial models as well. That might seem contradictory from the perspective of businesses built on charging for access to material. And yet, there are significant viable businesses on the Web that are based on open resources (e.g., in providing support services for Linux open operating systems). In education, one could imagine commercially successful service opportunities involving personalization, tutoring, and certification, built on a base of open resources. Other potential sustainability models include using advertisements and corporate

sponsorships. It is important to explore these and other models as a step toward realizing the potential of educational collaboration and continuous improvements on a wide scale.

2. NSF should launch a program to identify and demonstrate sustainable models for providing open educational resources, whose goal is to create mechanisms whereby educational materials developed by grantees will continue to have impact long after NSF support has ended. All materials development grants should include required discussions of sustainability, and this should be an important criterion in proposal evaluation.

In some cases, it may be appropriate for NSF itself to provide infrastructure for sustainability, similar to how the National Library of Medicine and its National Center for Biotechnology Information help ensure continued open access to the results of biomedical and life-sciences research, particularly that funded by NIH. In other cases, services within the data management and stewardship components of the cyberinfrastructure being developed under initiatives such as DataNet may meet these needs.

4.5 Harness the Deluge of Scientific Data

The amount of data in the world is at least doubling every year. As a result, it is becoming increasingly difficult to find relevant information and to extract meaningful knowledge from the ever-larger quantities of raw data. This challenge is present at every level of society, and it creates a huge demand for people with appropriate skills in navigating and processing information.

With the steady improvement of digital sensors and of the computers processing their data, every step of the scientific process is also changing. A new scientific paradigm, e-Science, is emerging, where computing techniques are an essential part of every step in the scientific workflow (Borgman, 2007; Hey & Trefethen, 2005). Inexpensive imaging sensors (CCDs) first revolutionized astronomy, and a decade later they fundamentally altered photography, turning

cameras into inexpensive, portable, and embedded devices. Gene sequencers and gene chips have enabled the assembly of the first human genome; in 10 years this technology will become part of everyday medical diagnostics. It is expected that in a few years the number of online sensors accessible through the Internet will exceed the number of computers today.

Modern scientific experiments use computers as an integral part of the data collection process. There is an emerging trend of large collaborations that are formed to undertake massive data collection efforts (virtual observatories) on every imaginable scale of the physical world, from elementary particle physics to material science, biological systems, environmental observatories, remote sensing of our planet, and observing the universe. These collaborations generate enormous datasets that are (or soon will be) made available online, for public use. Scientists will have this vast repository of data available to test their hypotheses and to combine data in novel ways to make new discoveries.

These virtual laboratories/observatories represent an entirely new way of approaching scientific problems. To be successful in these new approaches, scientists need to acquire a multitude of skills and ways of thinking. They have to be equally at home in their narrowly defined disciplines, in data management skills, and in computational skills that might require statistical analyses over billions of data points. These shifts also underscore the fact that the nature of scientific computing has become more data-centric than computing-centric (Bell, Gray & Szalay, 2006; Gray, Liu, Nieto-Santisteban et al., 2005).

We need novel ways of harnessing this data deluge and to turn it into new opportunities for learning, either involving new groups of people or engaging students in a totally different fashion. A recent trend to capitalize on people's interest in gaming has been to involve them in science-related activities that resemble gaming activities while delivering educational content (see inset on GalaxyZoo).

There is very little past expertise in this area, as the data deluge is a relatively recent phenomenon. We need to invent ways to teach and train the next generation as we go. Yet this is an area with enormous potential. The need for such skills cuts across all fields of science and much of society. This also raises an interesting question along a strategic continuum: where should our training focus? Should we solve these huge interdisciplinary problems by encouraging large interdisciplinary teams to work together, or should we increase the versatility of individuals and provide an ever-faster rate of retraining?

A paper on "antidisciplinary science," the science that precedes the emergence of new disciplines, argues rather forcefully that today we reward interdisciplinary teams, while the same cannot be said about individuals with a broad knowledge base (Eddy, 2005). In today's accelerating world, it is clear that we need to think more actively about how to provide a flexible enough scheme for science education to allow new, groundbreaking ideas to be translated into specific training programs for the next generation at an ever-faster rate. And little today in science is accelerating faster than computing, both using cyber-infrastructure and its methods for teaching about science.

4.6 Harness the Deluge of Learning Data

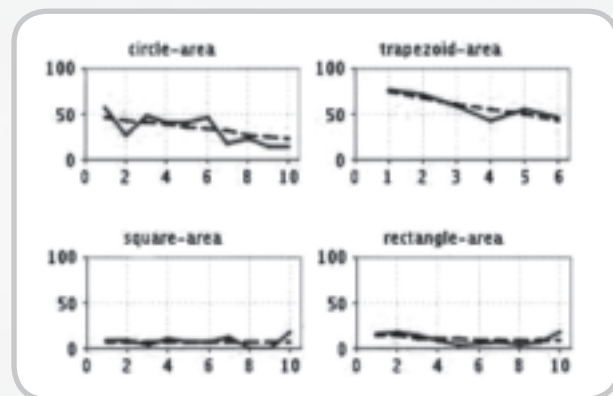
Scenario: To prepare for her algebra class in fall 2015, Ms. Washington gets online to access digital portfolios of her incoming students, which include records of their past mathematical successes and challenges. From experience she feels that some students have trouble learning algebra because they do not see it as interesting or important, whereas others have weaknesses in crucial prerequisites, like negative numbers. Because a good share of students' prior mathematics work has been done online in cyberlearning systems (simulations, virtual labs, math games, homework, tutors, online assessments, etc.), Ms. Washington has access to a rich set of quantitative and qualitative information about her students. The digital student portfolios provide summary statistics and representative examples of student past performance, and she knows to heed the recorded levels of cognitive and psychometric reliability of the different kinds of data available. Using these data, she identifies two risk groups among her incoming students: the disengaged and the unprepared. She then begins to plan activities specifically targeted to these groups, including selecting cyberlearning resources from the Internet such as collaborative math games for the disengaged and intelligent tutors to adaptively help the unprepared in their specific areas of need.

A large number of cyberlearning projects have been accumulating vast amounts of student data in a variety of domains and grade levels. These include interaction data from online courses,²¹ intelligent tutoring systems, virtual labs, and online assessments in subject matter, including elementary reading (Zhang, Mostow & Beck, 2007), middle school science (Buckley, Gobert & Horwitz, 2006), middle and high school mathematics (Koedinger & Alevan, 2007), and college-level science²² (Van Lehn, Lynch, Schultz et al., 2005; Yaron, Cuadros & Karabinos, 2005). There are also a large number of projects

collecting and analyzing video of classroom and informal learning interactions (Goldman, Pea, Barron et al., 2007). In the future, we expect increasing amounts of learner data available from formal and informal learning activities in the context of online chat, cell phones, games, and even toys. Further learning-relevant data from brain imaging and physiological sensors will also become increasingly available and useful, especially when coupled with other forms of behavioral data (Varma, McCandliss & Schwartz, 2008). Machine learning, psychometric, and cognitive modeling methods are increasingly being combined to discover improved cognitive-affective-psychometric models of student achievement and engagement through embedded assessment in cyberlearning systems.²³

Open-learning data repositories are beginning to emerge,²⁴ along with new computational techniques for analyzing such data. A new field of educational data mining is emerging, as indicated by the first conference on the topic in 2008.²⁵ NSF should encourage data contributions, data use, new algorithm development, and, most important, common standards for data storage so both data and algorithm sharing are facilitated.

The figures below are learning curves generated from an open repository of learner data²⁶ collected during student use of an intelligent tutor for geometry.



These learning curves show a change in student error rates (the y-axis) over successive

²¹ <http://www.cmu.edu/oli/>

²² See also <http://www.cmu.edu/oli/>.

²³ Machine learning has been employed to create automated embedded assessments systems that address both student cognitive achievement and affective engagement (Baker, Corbet, Roll et al., in press; Cen, Koedinger & Junker, 2006).

²⁴ Large-scale educational data can be found at <http://www.icps.umich.edu/AED>. Fine-grained student learning behavior data from recorded online, paper, and speech interactions in math, science, and language courses can be found at <http://learnlab.web.cmu.edu/dashop> (Koedinger, Cunningham & Skogsholm, 2008). Video data on classroom interactions can be found at <http://talkbank.org/data>, among other sites (Derry, 2007).

²⁵ <http://www.educationaldatamining.org/EDM2008>

²⁶ The Pittsburgh Science of Learning Center's DataShop can be found at <http://learnlab.web.cmu.edu/dashop>.

opportunities to practice and learn (the x-axis) in attempting to apply a geometry concept (e.g., circle-area) during problem-solving. The solid line shows average student data, and the dashed line shows predictions from a best-fitting cognitive-psychometric model. Notice how for the circle-area and trapezoid-area concepts, the student average error rate is initially quite high, but with practice and tutoring it improves. In contrast, the learning curves for square-area and rectangle-area indicate that students have little trouble right from that start (less than 10 percent error rate), but nevertheless get lots of practice (10 opportunities). Given such visualizations, it is not hard to conclude that a redesign is needed to reduce the unnecessary overpractice on some concepts and instead spend the valuable instructional time where it is needed. Just such a redesign was done and compared to the original version in a randomized controlled classroom study (Cen, Koedinger & Junker, 2007) that ran inside the technology and was essentially invisible to students and teachers. The results indicated a 20 percent savings of student time without any loss in learning, transfer, or retention outcomes.

4.7 Recognize Cyberlearning as a Pervasive NSF-wide Strategy

This may be the most important of all of the recommendations. All disciplinary directorates within NSF fund the development of resources—tools, software, learning objects, databases, etc.—that have either primary or secondary roles as educational materials. Just as cyberinfrastructure approaches now underpin disciplinary thinking about new research initiatives, we believe that cyberinfrastructure and cyberlearning ideas need to inform the work of the disciplinary directorates in shaping programs and evaluating proposals dealing with educational materials. One way to encourage this would be to conduct a series of workshops on cyberlearning in specific disciplines, much as NSF conducted an earlier series of workshops on the potential for cyberinfrastructure to advance research in specific disciplines.

5. Recommendations: NSF NSDL and ITEST Programs

5.1 Cyberlearning and the Evolving National STEM Digital Library (NSDL)

The National STEM Digital Library has explored some of the issues relevant to cyberlearning. NSDL is a large-scale project based on a vision that is now eight years old. An NSF review of the NSDL program is appropriate and timely, and we urge NSF to empanel such a review, with a charge that includes consideration of the future of NSDL in the context of recent developments in cyberinfrastructure and cyberlearning broadly.

NSDL offers evidence for two aspects of cyberlearning. Projects have explored searching and selection of materials from large numbers of collections of learning objects to meet the needs of educators and learners. NSDL is now in competition with commercial services such as Google that are much more comprehensive in the genres of material that they cover. Although these competing services cover learning objects specifically in less depth, the question of cost-benefit of the specialized NSDL portal needs periodic revisiting.

NSDL projects have also investigated the tools and human relationships needed to make the objects in the library useful. Effective ways to support users of materials developed by others remains an open question, especially given the complexities of the educational system. In thinking about the future of NSDL and the ways in which the NSDL investments can contribute to future cyberlearning programs, it is important to recognize that NSDL is not simply an information technology system; it has, for example, invested in developing a powerful human and organizational network to address challenges such as curricular linkage for learning materials.

Please see appendix 2 for further information about NSDL.

The NSDL program should be reviewed in the context of new developments in NSF cyberinfrastructure and cyberlearning initiatives and in light of the changing technological, social, and economic environments identified in this report.

5.2 Cyberlearning and the Evolving ITEST Program

The Innovative Technology Experiences for Students and Teachers (ITEST) program funds projects that explore issues in cyberlearning. The ITEST program is designed to increase student interest and proficiency in information technology and to guide more students into advanced study and careers. The program responds to current concerns and projections about shortages of STEM professionals and information technology workers in the United States and seeks solutions to help ensure the breadth and depth of the STEM workforce. ITEST supports the development, implementation, testing, and scale-up of models, as well as research studies to address these questions and to find solutions. There are a variety of possible approaches to improving the STEM workforce and to building students' capacity to participate in it.

An NSF review of the ITEST program is appropriate and timely, and we urge NSF to empanel such a review, with a charge that includes consideration of the future of ITEST in the context of recent developments in cyberinfrastructure and cyberlearning.



6. Summary Recommendations

This section summarizes the report's most important recommendations. The recommendations cut across the two clusters of strategies and opportunities. Taken together, these recommendations provide an initial strategy and steps for NSF to take in creating a cyberlearning infrastructure and initiating some powerful examples of how cyberlearning can transform systems to support education and learning. We believe that the climate is right in Washington and around the Nation for an aggressive and innovative program in cyberlearning. These five categories of recommendations complement work already going on in NSF and could serve as the basis for a significant initiative in the 2010 NSF budget. They also echo the major themes called out in the discussion above.

6.1 Help Build a Vibrant Cyberlearning Field by Promoting Cross-Disciplinary Communities of Cyberlearning Researchers and Practitioners

- Fund centers to use ICT to develop community-wide cyberlearning resources such as authoring environments, curriculum materials, professional development models, and assessments along with complementary talents needed for cyberlearning, e.g., researchers, classroom teachers, software designers, and school leaders.
- Establish funding of new summer training workshops and courses of study, integrative graduate education and research traineeships, postdoctoral fellowships, and research experiences for undergraduates devoted to building the cyberlearning capacities of the field. Recruiting and nurturing talent for research and teaching in these ways will ensure the diversity and breadth of the cyberlearning field. Industry and private foundation cosponsorships of such activities would be well warranted.
- Require cyberlearning projects to collaborate with teachers to create materials that build on their expertise and to test

innovations in varied settings.

- Support cyberlearning initiatives in professional development for in-service and preservice K–12 teachers. These programs need to be sustained over a minimum of 5 years to allow sufficient time for a cadre of well-trained and confident educators to become the role models and leaders.
- Utilize professional societies as an integral component of professional development because these organizations offer a cost-effective approach for reaching networks of committed educators (e.g., National Council of Teachers of Mathematics, National Science Teachers Association, National Society of Black Engineers, Association for Computing Machinery, Institute of Electrical and Electronics Engineers, International Society of the Learning Sciences).
- Launch a program that brings together technologists, educators, domain scientists, and social scientists to coordinate and draw upon repositories of cyberlearning data to advance our understanding of human performance.
- Publish a set of best practices for cyberlearning together with results from trials in diverse settings and recommendations about steps necessary for successful implementation.

6.2 Instill a Platform Perspective Into NSF's Cyberlearning Activities

- Fund the design and development of a common, open cyberlearning platform that supports a full range of teaching and learning activities, including assessment and analysis.
- Convene a panel of experts to delineate the requirements for such a platform and recommend possible hardware and software architectures.
- Require new technology projects to contribute interoperable components to the open platform rather than develop in isolation.

- Arrange for promising innovations to be utilized for the design of high-value resources that will be deployed on the platform for impact of nationwide scope.
- Maintain a tested collection of learning modules on the platform that teachers can easily integrate into their practice.
- Design effective supports for those using these modules to incorporate them into a full curriculum, customize them for specific goals, author new materials that incorporate effective pedagogy, align assessment with instruction, and create professional development that takes advantage of the same technologies.
- Establish a small office to monitor the growth and health of this infrastructure and to propose strategies to improve its health.
- Empanel reviews of the NSDL and the ITEST programs, with a charge that includes consideration of the future of the programs in light of recent developments in cyberinfrastructure broadly.

6.3 Emphasize the Transformative Power of ICT for Learning, From K to Gray

- Fund programs that tap the educational potential of the vast new flows of scientific data on the Web.
- Mount a program to stimulate the development of remote and virtual laboratories, including interactive simulations, and use of sensor networks and probeware as national resources, and to explore effective ways to design, deliver, and support this type of instruction.
- Fund research that highlights the educational use of information tools that operate seamlessly across formal and informal learning environments and across traditional computers, mobile devices, and newly emerging information and communications platforms. Assess ethical practices in the use of scientific data and of learner data in

cyberlearning by convening or coconvening a workshop.

- Fund foundational studies that restructure STEM knowledge domains using the interactive, representational, and data-mining capabilities of the cyberinfrastructure.
- Accelerate the development of the cyberlearning field by establishing synergistic partnerships with companies that are pioneering advances to the cyberinfrastructure and other foundations (e.g., Gates, Hewlett, Kaufmann, MacArthur, Mellon) and Government agencies that are funding related initiatives and programs.

6.4 Adopt Programs and Policies to Promote Open Educational Resources

- Require NSF grant proposals to include clear intellectual property statements about the deployment of educational materials funded by NSF.
- Require all educational materials produced with NSF funding to be made available on the Web using one of the family of Creative Commons licenses, to facilitate automated searching and processing and permit unrestricted reuse and recombination.
- Require grant proposals to contain a section that carefully considers strategies for the sustainability of the education materials funded by NSF.
- Have NSF launch a program to demonstrate sustainable models for providing open educational resources.

6.5 Take Responsibility for Sustaining NSF-Sponsored Cyberlearning Innovations

- Institute processes and mechanisms for sustaining innovations so that educational materials developed by grantees will continue to have impact long after NSF support has ended.
- Implement effective handoff and partnership programs so that valuable innovations remain in use and can be built upon. These programs should consider the role of industry, professional organizations, and other potential contributors.
- Coordinate cyberlearning activities across all of the NSF divisions to ensure that cross-fertilization—rather than duplication—of efforts occurs.
- Empower a Blue Ribbon Panel to oversee these activities by convening a standing panel of experts from across sectors and charging them with the responsibility to define, explore, and take responsibility for maintaining the aforementioned cross-sector partnerships for cyberlearning. Potential models to consider include the following:
 - The National Academy of Sciences Government–University–Industry Research Roundtable,²⁷ with a mission “to convene senior-most representatives from Government, universities, and industry to define and explore critical issues related to the national and global science and technology agenda that are of shared interest; to frame the next critical question stemming from current debate and analysis; and to incubate activities of ongoing value to the stakeholders.”
 - The Roundtable on Science and Technology for Sustainability,²⁸ which includes “senior decisionmakers from the

U.S. Government, industry, academia, and nonprofit organizations who are in a position to play a strong role in promoting sustainability.” Their goal “is to mobilize, encourage, and use scientific knowledge and technology to help achieve sustainability goals and to support the implementation of sustainability practices.”

Other recommended participants and related organizations include the following:

- The Learning Federation,²⁹ which is a partnership joining companies, universities, Government agencies, and private foundations to promote a national research plan to create radically improved approaches to teaching and learning enabled by information technology
- Educause,³⁰ which is a nonprofit association whose mission is to advance higher education by promoting the intelligent use of information technology
- MacArthur Networks,³¹ which are interdisciplinary research networks, “research institutions without walls,” addressing a variety of topics
- The MacArthur Foundation’s Digital Media and Learning³² effort to fund research and innovative projects focused on understanding the impact of the widespread use of digital media on our youth and how they learn

As we realize new models for collaboration, the new organizations need to be chartered and empowered to execute their mandates—namely, the sustainability of learning technology innovations and solutions needs to be an ongoing priority. Once sustainability is achieved, it is then important to ensure the careful transition from startup to maintenance mode, ensuring a handshake instead of a handoff.

²⁷ <http://www7.nationalacademies.org/guir/>

²⁸ <http://sustainability.nationalacademies.org/roundtable.shtml>

²⁹ <http://www.learningfederation.org/>

³⁰ <http://www.educause.edu/about/>

³¹ http://www.macfound.org/site/c.1kLXJ8MQK/H/b.948165/k.E3C/Domestic_Grantmaking___Research_Networks.htm

³² <http://digitalllearning.macfound.org/site/c.enJLKQNFIG/b.2029199/k.BFC9/Home.htm>

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Appendices

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Appendix 2. Further Information About NSDL

It is important to understand what the National STEM Digital Library (NSDL) is and is not; the name can be confusing. Primarily, NSDL is an organizing and descriptive mechanism and access portal to a range of collections of learning resources, mainly “learning objects” (as opposed to the kinds of materials that are coming out of more recent attempts to capture entire courses in video or audio, or to make available course materials through open courseware initiatives). The presumed users of NSDL are mainly teachers, although certainly students (and parents, especially in the case of home schooling) make substantial use of the system. NSDL does not finance the creation of, nor “own,” the learning objects to which it provides access, although the possibility of an archival preservation role for these collections involving NSDL has been raised. NSDL has been agnostic as to whether the learning materials to which it provides access are entirely free, Creative Commons licensed, or offered for a fee. NSDL is not the exclusive access mechanism for the collections it organizes: some can be found through tools such as Google, and others have very strong disciplinary and educational communities that are directly linked to the underlying collection (such as Digital Library for Earth System Education). In some cases, other (non-NSDL) NSF funding programs have contributed to the creation and maintenance of content resources organized by NSDL.

NSDL covers learning objects. It does not cover the published scientific and scholarly literature or the gray literature (such as technical reports and preprints); it does not cover scientific, engineering, and other scholarly data resources; and it does not systematically cover full-scale open courses and courseware. All of these materials need to be available in the cyberinfrastructure to support both research and teaching and learning—and they need to be extensively interconnected in new and complex ways (for example, scholarly articles and underlying data are becoming much more intimately linked.). Responsibility for all of this content and its availability in the cyberinfrastructure is diffuse and in some cases unclear, but the important point here is that this has never been part of the NSDL program. And it needs to be addressed, in support of both research and education. For datasets, NSF has made a start with its data-oriented programs within the cyberinfrastructure initiatives. University research libraries, national libraries (in particular, the National Library of Medicine), scholarly societies, and disciplinary researchers are working in many of these areas.

Appendix 3. NSF Reports Related to Cyberlearning

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