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 NSF[3] 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.

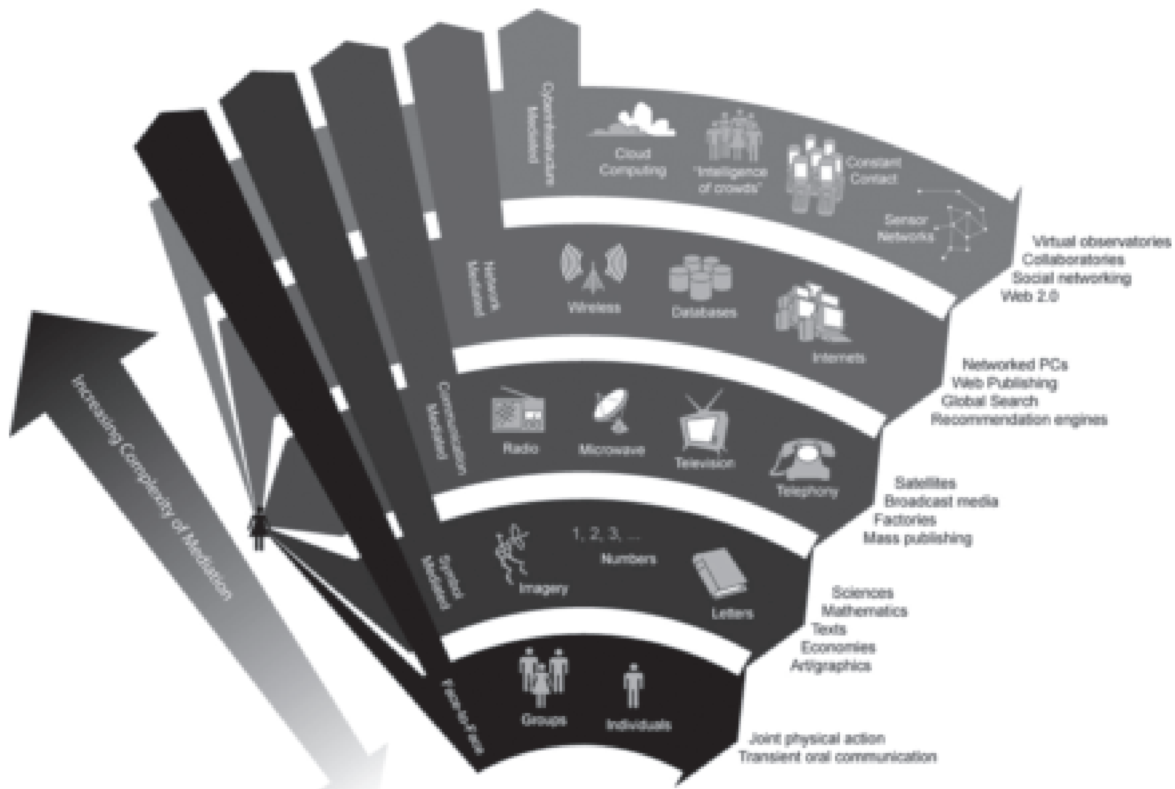

Figure 1. Advances in Communication and Information Resources for Human Interaction (Roy Pea & Jillian Wallis).

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" (Prahalad & 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.


CYBERLEARNING