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 cyberinfrastructure 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 cyberinfrastructure-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 cyberinfrastructure 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 Cyber-learning 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, Airoldi, 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 Cyber-learning 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 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.

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).

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 Cyber-learning 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 thermo-dynamics) (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 revisioned 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 collaboratories 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 IdeaLab[13] 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 Competition[15] 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 NSFNet[16] 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 connected[17]—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 2007[19] 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?

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