Cyberinfrastructure for Education and Learning for the Future:

A VISION AND RESEARCH AGENDA

Computing
Research
Association

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Foreword

This report is the result of a series of workshops organized by the Computing Research Association and the International Society of the Learning Sciences with support from the National Science Foundation (Grant No. REC-0449247).

The purpose of the workshop series was to explore where we are in the application of pervasive computing power to education, and where we need to be. In particular, the intent was to develop a map of where NSF can strategically place its resources in creating the learning environments of the future.

The four workshops were:

1. Modeling, Simulation and Gaming Technologies Applied to Education, September 27-29, 2004.
2. Cognitive Implications of Virtual or Web-enabled Environments, November 30-December 1, 2004.
3. How Emerging Technology and Cyberinfrastructure Might Revolutionize the Role of Assessment in Learning, February 16-17, 2005.
4. The Interplay Between Communities of Learning or Practice and Cyberinfrastructure, March 24-25, 2005.

This report is based on the results of these four workshops and was written by Shaaron Ainsworth, Margaret Honey, W. Lewis Johnson, Kenneth Koedinger, Brandon Muramatsu, Roy Pea, Mimi Recker, and Stephen Weimar as representatives of the four workshops. A list of the workshops' participants appears in Appendix A. The report was edited by CRA staff Andrew Bernat, Jean Smith, and Daniel Rothschild.

The report is posted on the CRA website (http://www.cra.org/reports/cyberinfrastructure.pdf). To request a hard copy, send an e-mail to info@cra.org.

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Executive Summary

There are troubling signs that the United States is failing to train adequate numbers of students for careers in science and technology, or to develop the broad scientific and technological literacies that are necessary for full participation in a democratic society. To meet this challenge, we propose an initiative to develop the *Cyberinfrastructure for Education and Learning for the Future,* or *CELF* (pronounced "self").

We envision a Cyberinfrastructure that provides: 1) unprecedented access to educational resources, mentors, experts, and online educational activities and virtual environments; 2) timely, accurate assessment of student learning; and 3) a platform for large-scale research on education and the sciences of learning. CELF will transcend the boundaries of formal education, informal learning, and lifelong learning. Learners of all ages will be able to reap the full benefits of the nation's scientific Cyberinfrastructure by engaging with scientific models, simulations, data sets, sensors and instruments. Moreover, the new educational Cyberinfrastructure will make it possible to collect and analyze data continually from millions of educational activities nationwide over a period of years, enabling new advances in the sciences of learning and providing systematic ways of measuring progress at all levels.

Cyberinfrastructure has significant potential to radically influence educational practice. We note that it is common to overestimate the near-term effects of technology and to underestimate its long-term consequences. Given the generative importance of education, we must not view the impact of Cyberinfrastructure on education as merely a side benefit of efforts aimed at practicing scientists. The fundamental activities of design, creation, implementation and research concerning educational and learning processes supported by technologies pose a unique set of challenges for Cyberinfrastructure that merit investigation in their own right. For example, CELF must be designed to collect and manage large amounts of data about learners and their activities, and thus must address concerns of privacy, security, and ownership of potentially sensitive data. It must yield technical solutions that are informed by advances in learning sciences research and are appropriate for educational contexts. It must be coupled with research evaluating the effects of CELF on learning to ensure that the benefits can be achieved in a systematic and replicable fashion. Professional development is needed to ensure that teachers can use CELF technologies effectively to promote learning and sustain motivation.

The National Science Foundation (NSF) occupies a unique position among federal agencies that fund science, technology, engineering, and mathematics (STEM) education research and development. By bridging education and the scientific, engineering, and mathematical disciplines that are at the Foundation's core, NSF initiatives are able to draw upon advances in basic cognitive and social sciences research, while integrating new content and exploring the ways in which new technologies can enhance the kinds of learning opportunities available to teachers and students. It is precisely this process that must remain at the core of NSF's investment in next-generation technologies.

This report investigates the following issues relating to CELF:

1. **Blending Formal and Informal Learning:** How does CELF transcend the conventional boundaries of school-based education to leverage learning taking place across the contexts established by time, space and social arrangements (e.g., non-school activities involving family, community, work and play)? How does it differ from these contexts?
2. **Lifelong Learning Chronicles:** What forms of rich qualitative and quantitative data need to be collected to dynamically inform the multitude of education stakeholders?
3. **Teaching Through the Cyberinfrastructure:** What are the new images of teaching and teachers afforded by CELF?
4. **Communities of Learners:** How can CELF support and transform communities of learners?

Lastly, the report examines some of the policy implications of the CELF initiative, including the risks of not attending to this initiative, privacy and security issues, equity and access issues, and dissemination, including informing the public and decision makers about its potential.

1. Introduction

During the past three decades, a radical and transformative technological revolution has unfolded that has resulted in fundamentally new ways of doing business, conducting research, communicating, and seeking and exchanging information.

In the science and engineering fields, computational technologies are changing the ways in which scientific research is carried out. Modeling and simulation tools, along with wide-scale deployment of grid technologies, allow scientists and engineers to work in ways that were not previously possible. Networking tools facilitate the exchange of ideas and scientific instrumentation and data across time, distance, and disciplines, making distributed-knowledge environments an essential component of research-based enterprises. Innovation is more of a necessity now than ever before. And yet a number of recent reports make it clear that the United States is losing ground on key indicators of innovation and progress (e.g., Council on Competitiveness[1] and Atkins, 2003[2]). Pre-college education, in particular, is lagging well behind its mandate to educate all children to higher standards, especially in areas that prepare students for careers in science, technology, engineering, and mathematics (STEM).

In a recent speech before the Education Writers Association, Secretary of Education Margaret Spellings stated: "Our nation's leadership position in the world is being challenged. For example, 38 percent of bachelor's degrees in China were awarded in engineering as opposed to less than 6 percent in the U.S. And in the decade from 1990 to 2000, India increased its number of students enrolled in college by 92 percent" (Spellings, 2005). Meanwhile, science and engineering enrollments at the college and university levels are showing troubling signs of decline. American universities are facing increasing competition from overseas institutions for the best students, resulting in declining enrollments of foreign students.[3] Domestic enrollments are not expanding to fill the gap; in fact, some science and engineering fields such as computer science have experienced precipitous declines in enrollment.[4] If the country does not find ways of increasing college enrollment and retention in science and engineering, the economic competitiveness of the United States will be at risk.

International indicators of pre-college students' progress paint a more troubling picture. Results from the Third International Mathematics and Science Study (TIMSS) show that mathematics performance among U.S. eighth-grade students is lower than that of fourteen other countries (Mullis, Martin, Gonzalez, and Chrostowski, 2004), putting them well behind the highest-performing countries.

Clearly, the challenges facing "pre-K to gray" education are of magnitudes that require grand and ambitious strategies, not only to halt the decline in U.S. students' progress, but also to reinvigorate the system to lead the world in innovation and excellence. Historically, the National Science Foundation (NSF) has been at the forefront of supporting research and development efforts that lead to significant advances in science and industry. Its role in supporting innovation in the K-12, undergraduate, and graduate sectors has been equally significant. For instance, The National Science Digital Library (NSDL) was created by NSF to provide organized access to high-quality resources and tools that support innovations in teaching and

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[1] See http://www.compete.org/ for these indicators.

[2] Atkins, D.E. (Ed.). (January 2003). *Revolutionizing Science and Engineering Through Cyberinfrastructure: Report on the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure*. http://www.cise.nsf.gov/sci/reports/atkins.pdf (Downloaded June 15, 2005).

[3] Dillon, S. (2004). "U.S. Slips in Attracting the World's Best Students." *The New York Times*, Dec. 21, 2004.

[4] Frauenheim, E. (2004). "Computer Science Turns Off Students." CNET News.com, August 12, 2004.

learning at all levels of STEM education (Zia, 2001).[5] The library currently contains more than 800,000 STEM educational resources from 500 partner libraries. NSF funding also helped to create Cognitive Tutor Algebra, a full-year algebra course based on cognitive psychology theory and artificial intelligence technology that is associated with increased student achievement[6] and is now in regular use in 2,000 U.S. schools (see http://carnegielearning.org). Another example of NSF's influence across the STEM curriculum includes the Technology Enhanced Learning in Science (TELS) Center (http://www.telscenter.org/) at one of the NSF Centers for Learning and Teaching. TELS is building upon NSF-funded research to support science learning mediated by Web-based technologies, such as modeling and simulation, for all science courses in grades 6-12.

The objective of *The CELF Initiative* to create the *Cyberinfrastructure for Education and Learning for the Future* is to ensure that "pre-K to gray" learning and teaching are informed by 21st century technological developments, learning sciences, and STEM research. We envision a CELF that: 1) could support unprecedented access to educational resources, mentors, experts, and online educational activities and virtual environments; 2) provides timely, accurate assessment of student learning; and 3) provides a platform for large-scale educational research. Learners of all ages would be able to reap the full benefits of the nation's scientific Cyberinfrastructure by engaging with scientific data sets, instruments, models, and simulations. Moreover, the new educational Cyberinfrastructure will make it possible to collect and analyze data continually from millions of educational activities nationwide over a period of years, enabling new advances in the sciences of learning and providing systematic ways of measuring progress at all levels. However, creating such an infrastructure in a way that meets the needs and respects the rights of all participants in the educational process requires that significant technical challenges be addressed.

Although the envisioned Cyberinfrastructure alone cannot cure the problems of lagging performance and inadequate enrollments in STEM fields, it could have a significant impact if it is properly informed by learning sciences research and linked to educational practice. By transcending the boundaries of formal and informal learning—and by helping students experience what it is like to engage in scientific inquiry, evidence-based argumentation, and engineering practice—we can engage their interests and motivate them to pursue scientific and technical careers. At the very least, we can encourage them to participate more meaningfully in deliberations and decision making involving the STEM disciplines that are essential to the democratic ideals of an educated society. Having more quantitative data available on learner performance will make it possible to optimize each learner's educational experience, identifying strengths and needs and providing online or real-time support as it is required. The ability to respond and provide remediation based on individual needs should improve the performance of educational systems at all levels.

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[5] Zia, L. (2001). Growing a national learning environments and resources network for science, mathematics, engineering, and technology education: Current Issues and Opportunities for the NSDL Program. Retrieved 17 July, 2003, from http://www.dlib.org/dlib/march01/zia/03zia.html.

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

More than three decades of investment in multiple pre-college R&D programs have generated valuable lessons that can be used to inform this next generation of education funding at all levels. These lessons include:

- Instructional approaches based on solid science on how people learn can yield large gains in student learning and engagement.[7, 8, 9]
- The claim that technology holds the promise of radically changing the learning of science, technology, engineering, and mathematics should be pursued with a clear understanding of the impact of the fundamentally cultural, social, and contextual nature of both learning and technology use. Professional training ideally will support teachers to further solidify their own content knowledge and skills, as well as increase their ability to effectively impart this knowledge to their students. The power of new technologies to advance learning will not be fully realized without *close attention to the social context in which those technologies are used*.[10]
- Teachers need pre-service and in-service professional development on using technology, but most importantly on how best to use it to support the acquisition of domain knowledge and reasoning skills, metacognitive development, and sustained interest and motivation.[11] The need for highly qualified teachers is well documented,[12] and Cyberinfrastructure technologies and methodologies will place new demands on their talents.
- Education and educational technology use must keep up with ever-changing economic, social, and cultural needs.
- Assessment practices must be adapted to these changes and better represent the true needs of society, and not simply pursue an uninvestigated repetition of K-12 formal education.[13] Cyberinfrastructure offers the potential to improve or reinvent assessment practices. Given the strong impact the nature of assessment has on how and what students learn, testing must be adapted to emphasize the opportunities that Cyberinfrastructure offers for allowing students to go beyond *knowing* science to *understanding* science.

There are also important concerns for the future:

- As STEM research becomes increasingly collaborative, distributed, and dependent upon access to large amounts of computational power and data, students as well as teachers and educational decision makers at all levels will need to learn how to *think with data*—using diverse forms of data, information resources, tools, and services in many different fields of study to support making a broad range of decisions. They will need to become proficient in navigating a rich universe of data resources;

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[7] Bransford, J. D., Brown, A., & Cocking, R. (2000) (Eds.), *How People Learn: Mind, Brain, Experience and School, Expanded Edition.* Washington, DC: National Academy Press.

[8] Clark, R. C., and Mayer, R. E. (2003). *e-Learning and the Science of Instruction : Proven Guidelines for Consumers and Designers of Multimedia Learning.* San Francisco: Jossey-Bass.

[9] Bransford, J., Vye, N., Stevens, R., Kuhl, P., Schwartz, D., Bell, P., Meltzoff, A., Barron, B., Pea, R., Reeves, B., Roschelle, J., & Sabelli, N. (2005, in press). Learning theories and education: Toward a decade of synergy. In P. Alexander & P. Winne (Eds.), *Handbook of Educational Psychology, 2nd edition.* Mahwah, NJ: Erlbaum.

[10] For example, Corbett, A. T., Koedinger, K. R., & Hadley, W. H. (2001). Cognitive Tutors: From the research classroom to all classrooms. In P. S. Goodman (Ed.), *Technology-Enhanced Learning: Opportunities for Change* (pp. 235-263). Mahwah, NJ: Erlbaum.

[11] Wallace, R., Kupperman, J., Krajcik, J., & Soloway, E. (2000). Science on the Web: Students online in a sixth-grade classroom. *Journal of the Learning Sciences, 9*(1), 75-104. Recker, M., Dorward, J., Dawson, D., Halioris, S., Liu, Y., Mao, X., et al. (2005). You Can Lead a Horse to Water: Teacher Development and Use of Digital Library Resources. In *Proceedings of the Joint Conference on Digital Libraries* (pp. 1-9). NY, NY: ACM.

[12] For example, Darling-Hammond, L. (2001). Who is teaching our children? The challenge of staffing our schools. *Educational Leadership, 58* (8).

[13] For example, Pellegrino, J. W., Chudowsky, N., and Glaser, R. (Eds.). (2001). *Knowing What Students Know: The Science and Design of Educational Assessment.* National Research Council, Washington, D.C.: National Academy Press.

in engaging with statistics, probability and evidence-based argumentation; and in discerning the authenticity, quality and reputation of these data sources. Emerging tools and frameworks for interactive and dynamic visualizations of patterns in data will be integral to these new literacies for thinking and decision making.

- Equity issues must remain a central concern in the CELF R&D agenda. Today, students do not have equal access to high-quality instructional resources, nor do they have equal access to highly qualified teachers, particularly for higher-level science and mathematics courses,[14] as recognized, *inter alia*, by the Taxpayer-Teacher Protection Act of 2004.[15] With the increasing diversity of native languages in the nation's schools and workplaces, the challenges of meeting multilingual needs are an important aspect of this access problem.[16] Ensuring that materials are designed to address the learning challenges of underserved populations and communities is a national imperative.
- We know too little about the second-order effects that emerge when networked systems create impacts that were both unplanned and unanticipated.[17] This emerging issue in complex systems will have its own special shape in learning and teaching environments that engage ubiquitous computing across formal settings of school and informal settings in home and community. For example, how will concerns about data and usage privacy and accessibility be resolved across these boundaries? How will the large amount of learning that takes place in informal and workplace settings, and is increasingly incorporating digital forms, be reconciled with formal schooling and assessment?

In keeping with scientific trends and developments, we propose CELF as an expanded vision of Cyberinfrastructure R&D. In this vision, CELF will provide learners, educators, and other stakeholders with access to, and the ability to participate in, long-lived, large-scale educational experiences, encompassing real-world experiential learning, simulation, modeling, educational games, automated assistance from virtual peers and intelligent tutors, and Web-based access to authentic learning resources and scientific data. It will include tools that facilitate the creation and adaptation of learning experiences with digital resources, and data collection and analysis tools that make it possible to evaluate a learner's progress on a continual and longitudinal basis. CELF will make possible the compilation, analysis, and distillation of unprecedented amounts of human performance and learning data, with built-in provisions for data protection, privacy, and control. It will provide a foundation for science learning that is computationally enabled and empirically based, coupled with innovations in educational practice.

Consider the following scenario. The context of this particular image is a "serious game," that is, an interactive experience that promotes learning and is entertaining.

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[14] California Council of Science and Technology (April 2002). *Critical Path Analysis of California's S&T Education System.* ISBN 1-930117-21-3. (Downloaded July 6, 2005 from http://www.ccst.us/ccst/pubs/cpa/cpadex.html).

[15] HR 5816, 108th Congress of the United States, 2004.

[16] For example, Fradd, S. H., & Lee, O. (1999). Teachers' roles in promoting science inquiry with students from diverse language backgrounds. *Educational Researcher, 28*(6), 4-20, 42, and Lee, O., & Fradd, S. H. (1998). Science for all, including students from non-English language backgrounds. *Educational Researcher, 27*(3), 12-21.

[17] Examples include voice-over-Internet phone networks (VOIP) developed to avoid personal long-distance telco charges that are now transforming the economics of business communications; computer spam and viruses and the large global businesses that were developed to protect computer enterprises and users from them; peer-to-peer networking architectures developed for personal music file-sharing have spawned new legitimate broadband businesses; and the Internet itself morphed into a commercial medium (e.g., EBay, Amazon, Yahoo!, Google) from its origins as a military communications network distinct from telephone networks.

Learners cooperate in designing and conducting a mission to Mars, in the context of a game-based simulation. In the course of the project they carry out a variety of STEM-related learning activities, spanning physics, chemistry, biology, engineering and mathematics. These become springboards for seeking other learning resources outside the game, and collaborating with other learners in online working groups. Learners access online science and engineering data sets and models in order to compare their predictions against results from space scientists. They receive guidance in inquiry skills, metacognitive learning skills, and collaboration skills. The game itself is constructed and adapted through the collaborative efforts of the participating learners. In his earth sciences course, John, for example, studies terrain data from Mars Rover missions and creates a model of the Martian terrain to be explored by others. Manuela, in her high-school engineering class, designs an autonomous rover vehicle to collect geologic samples and constructs a simulation of her rover design for use in the mission. She can then compare her model's performance in the simulation against records of actual Mars Rover missions. Sherry, the teacher, is assisted by virtual assistant teachers (intelligent tutors) embedded in the game that help her monitor learner progress and offer guidance and challenges. One of Sherry's virtual assistants reports that Manuela is having difficulty getting the controller of her virtual robot to work, and is not availing herself of online resources, so Sherry suggests that she discuss her design with an online community of robot enthusiasts. Data collected from learner performance within and surrounding the game provide the teacher with documentation and evidence of learning progress relating to curriculum standards and goals. In some contexts this may replace the need for standardized tests, but in others the teacher already has sufficient evidence to predict that the learners will meet the required standards.

Serious games such as this are becoming increasingly common in public policy, healthcare, and military training,[18] as well as for corporate training and all levels of education.[19] CELF can help turn serious games from narrowly focused experiences created for special purposes to a broad-based, long-lived experience.

Such research is inherently multidisciplinary, involving the entire NSF, STEM professionals in partnership with computer and information science and engineering (CISE), social, behavioral and economic (SBE) researchers, and a full range of educational researchers (e.g., learning scientists, sociologists, psychologists and cognitive scientists, and teacher educators). Furthermore, given the integrated and long-term nature of such an endeavor, every effort must be made to ensure that CELF research is coordinated and inclusive.

It is expected that learning and education through CELF should be increasingly personalized, interactive, and tailored to meeting a learner's curricular, motivational, metacognitive and social needs. Personalized learner interactions should be realized not only in formal classes with "conventional" computers, but also in informal educational settings where they are mediated through a range of personal ubiquitous devices. To meet individual needs, assessment will be continuous and dynamic, aimed at monitoring and supporting learners to develop their cognitive and metacognitive skills. Such learning is not the right of a privileged, digitally and educationally sophisticated few, but instead is inclusive and accessible for all.

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[18] Wertheim, M. (2004). A virtual camp teaches soldiers in Arabic, and more. *The New York Times*, July 6, 2004.

[19] In 2004-05, major activities have included the Serious Games Summit at the 2004 Game Developers Conference, a panel at SIGGRAPH-2005, and the forthcoming DC-based Serious Games Summit in Autumn 2005. Another phrase to describe this category is "social impact games," those that are entertaining games with non-entertainment goals, and for more than 200 examples, see: http://www.socialimpactgames.com/.

To realize this vision, we identified five issues that illustrate the potential of the Cyberinfrastructure for transforming educational practice, given the appropriate conditions, that will need to be addressed.

1. **Blending Formal and Informal Learning:** How does the Cyberinfrastructure transcend the conventional boundaries of school-based education?
2. **Lifelong Learning Chronicles:** How do we develop a rich qualitative and quantitative record of learning over time in a way that dynamically informs a multitude of stakeholders?
3. **Teaching Through the Cyberinfrastructure:** What are the new images of teaching and teachers afforded by the Cyberinfrastructure?
4. **Communities of Learners:** How can the Cyberinfrastructure support and transform communities of learners?

The final issue considered is what policy and societal changes might be needed to ensure that the vision presented in these sections can be realized.

5. **Educational Policy and the Cyberinfrastructure:** What changes in processes, policies, and support are necessary to achieve those educational experiences?

Each issue is discussed in the following chapters 2 through 6. Concluding remarks appear in chapter 7, followed by a list of workshop participants in Appendix A and a list of questions sent to participants prior to each workshop in Appendix B.

2. Blending Formal and Informal Learning:

Transcending the Conventional Boundaries of School-Based Education

Cyberinfrastructure for Education and Learning for the Future (CELF) will change the way learning takes place both inside and outside the classroom, blurring the distinctions between the two.[20] Technology-mediated learning will take place in the context of computationally augmented real-world environments, online communities of practice, interactive virtual environments, games, simulations, models, and audio/video/IM/SMS communications—not just in classrooms. Learning occurs now in these milieus, but largely independent of one another and uninformed by educational research. It is increasingly apparent that informal and lifelong learning is the key solution to equipping people with the evolving knowledge and skills that will be needed to adapt to the continuously changing nature of society.

Consider the following scenario for its image of blending formal and informal learning:

> *The classes John and Manuela attend take mobile devices [including a phone, camera, personal digital assistants (PDAs), embedded sensors, location-aware global positioning systems (GPS)] into a local town. They explore the town, learning about its history over the past 100 years and the people who have lived in the town, as well as its physical and political geography. As they reach hotspots they receive specific information, which will be different according to different learner profiles. John's PDA speaks some of this information once it detects that he is having difficulty reading some of the texts and is becoming distressed by his inability to keep up. The students take photographs, record audio messages and video and take sensor readings of temperature, pollution, and humidity. Manuela has a particular interest in geology and is collecting soil samples. When her digital agent tells Manuela that her friend Beth is near the town museum, she asks Beth to check out what's available. The students share the information they are collecting with each other and with other students back in school. The next day, the whole class interacts with these data to collate, represent and analyze them. They compare their data to those collected by students in other schools and in previous years. Manuela sends some of her results of the geological survey back to the museum where it is incorporated into the exhibition. Several weeks later, a proud Manuela takes her parents back to the museum to see the results of her work.*

We need to integrate the best aspects of technology-mediated informal learning into classroom learning, making it possible for in-class and out-of-class learning to support each other to a greater extent than they do now. Furthermore, the opportunities for learning are not limited to a classroom, but can occur in any place and at any time. They do not suddenly stop when a school bell rings or the semester ends. To effectively achieve this vision, innovations in the Cyberinfrastructure itself will be needed, as well as coordinated multidisciplinary and interdisciplinary research in how best to exploit the potential of the new Cyberinfrastructure.

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[20] For example, see Barron, B. (2004). Learning ecologies for technological fluency: Gender and experience differences. *Journal of Educational Computing Research, 31*(1), 1-36.

Two important areas for CELF—1) portable and personal technologies, and 2) virtual learning environments, including virtual resource centers and digital libraries, games, simulations and modeling—are identified below and characterized in some detail.

Portable and Personal Technologies

Portable and personal technologies are a ubiquitous part of modern life. For example, Prensky (2005)[21] estimates that there are 1.5 billion mobile phones in the world (no doubt an underestimate by the time this report is published), and 80 percent of the world's population lives within range of a cellular network.[22] In some countries, particularly in Europe, mobile penetration is at 100 percent; in the United States, 40 percent of junior high students and 75 percent of high school students have mobile phones.[23] Furthermore, the processing power of top-end mobile phones and PDAs is only a decade behind the computing power of desktop computers. For current and future generations of learners, it is increasingly likely that their main interaction with the digital world will be through such devices. Consequently, one of the main challenges facing educators is to move from the prevailing view of mobile technologies as disruptive devices that have no place in a classroom to understanding how best to exploit the substantial opportunities that such devices offer.

We are only beginning to understand the opportunities that portable and personal technologies—known as "mobiles"—provide for learning.[24] However, they have a number of distinct characteristics. They are lightweight and highly portable, encourage communication and connectivity, enable new forms of collaborative learning, can respond or gather information from the environment in a time- and location-aware manner, and can be personalized to meet different learners' requirements.[25,26] These characteristics of mobiles support many different innovative learning practices:

- They can be used as classroom response systems to gather student responses, showing anonymized individual views as well as aggregate data.[27]
- They can provide mixed reality tours of museums, galleries, and the wider environment. For example, the Archeoguide project aims to provide an augmented reality reconstruction of the ruins in ancient monuments, which are adapted to the specific interests of each visitor.[28]

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[21] Prensky, M. (2005). What can you learn from a cell phone? Almost anything! *Innovate* 1 (5). http://www.innovateonline.info/index.php?view=article&id=83 (accessed June 7, 2005).
[22] "Mobile Phones and Development: Less is More," *The Economist*, North American edition, July 7, 2005.
[23] NOP World (2005). Backpacks, lunch boxes and cells? . . . Nearly half of US teens and tweens have cell phones, according to NOP World mKids study. March 9. http://www.nopworld.com/news.asp?go=news_item&key=151 (accessed June 7, 2005).
[24] Pea, R. D., & Maldonado, H. (2005, in press). WILD for learning: Interacting through new computing devices anytime, anywhere. In K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences*. New York: Cambridge University Press.
[25] Roschelle, J., & Pea, R. D. (2002). A walk on the WILD side: How wireless handhelds may change computer-supported collaborative learning (CSCL). *The International Journal of Cognition and Technology*, 1(1), 145-168.
[26] Naismith, L., Lonsdale, P., Vavoula, G. & Sharples, M. (2005). *Literature Review in Mobile Technologies and Learning*. A Report for NESTA Futurelab. http://www.nestafuturelab.org/research/lit_reviews.htm#lr11 (accessed June 7, 2005).
[27] Penuel, W.R., Roschelle, J., Crawford, V., Shechtman, N. & Abrahamson, L. (2004). *Workshop report: Advancing research on the transformative potential of interactive pedagogies and classroom networks.* Menlo Park: SRI International. http://ctl.sri.com/publications/downloads/CATAALYST_Workshop_Report.pdf (downloaded June 15, 2005).
[28] Papageorgiou, D., Ioannidis, N., Christou, I., Papathomas, M., and Diorinos, M. (2000). ARCHEOGUIDE: An augmented reality based system for personalized tours in cultural heritage sites. *Cultivate Interactive*, 1. http://www.cultivate-int.org/issue1/archeo/ (downloaded June 7, 2005).

- They allow learners to take part in participatory simulations and games. For example, in the Savannah project,[29] school children play the part of lions roaming around their environment (a school playing field) using location-aware PDAs. They learn how to mark their territory (with scents indicated on PDAs), collaborate to hunt large prey (when they reach a hotspot they may be told they are hungry or that there is an elephant nearby), and retreat to a den to reflect on success and failure. By becoming lions, children have many opportunities to understand the reasons for lions' behavior. Similarly, the Environmental Detective project uses related technology to help learners understand the sources of water pollution.[30]

- They can support teachers in their professional practice. Perry (2003)[31] found the practical features of PDAs—such as size, synchronization features and battery life—helped school administrators and teachers coordinate meetings, assess attendance and truancy, and organize lesson plans. Tatar et al. (2003)[32] emphasize the importance of teacher involvement in the design of these learning technologies.

- They may be able to reach learners who are disadvantaged by the digital divide: Naismith et al. (2005) report that in Europe up to 80 percent of young homeless people have access to mobile phones, and a new family of extremely inexpensive cell phones are already patented and being manufactured (Prensky, 2005). The M-learning project[33] is exploring how mobile phones can improve basic literacy and numeracy skills for disadvantaged young people. Typical applications include the use of phones to provide games, multimedia messaging to add visual and audio material to Web-based graphics, and text messaging to supply quizzes.[34] It is encouraging that initial user trials report not only increased skills, but an increased appreciation for education.

- They also have a role to play in assessment as well as learning. In the United Kingdom, eVIVA is exploring innovative ways of assessing the Information and Communication Technologies (ICT) capabilities of students. Students compile online portfolios of their ICT work to show what they know and can do, the processes they have used, and the decisions they have made. Annotating their work gives them an opportunity to show their thinking. Teachers and other students can then provide feedback. Once students have completed their portfolios, they have a unique assessment—their viva[35]—which they can take on their mobile phone. In the United States, Wireless Generation's mCLASS mobile technology, with a special focus on early literacies with its DIBELS software, has been used by 75,000 teachers in 43 states for time-saving handheld assessments with more than one million K-3 students.[36]

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[29] Facer, K., Joiner, R., Stanton, D., Reid, J., Hull, R., and Kirk, D. (2004). Savannah: mobile gaming and learning? *Journal of Computer Assisted Learning, 20, 399–409*.

[30] http://www.educationarcade.org/gtt/

[31] Perry, D, (2003). *Handheld computers in schools.* http://www.becta.org.uk/page_documents/ research/handhelds.pdf (downloaded June 7, 2005)

[32] Tatar, D., Roschelle, J., Vahey, P., & Penuel, W. R. (2003). Handhelds Go To School: Lessons Learned. *IEEE Computer, 36*(9), 30-37.

[33] Attewell, J (2005) *Mobile technologies and the m-learning project* http://www.lsda.org.uk/files/pdf/041923RS.pdf (downloaded June 7, 2005).

[34] See http://www.m-learning.org/

[35] See http://www.eviva.tv/

[36] See http://www.wirelessgeneration.com/

- They can support learning by allowing individuals involved in informal science to engage with the scientific enterprise. For example, citizens around the country can contribute their observations and counts of birds to support a national bird census,[37] or participate in other scientist-citizen partnerships such as Salmon Watch programs where volunteers contribute data from throughout a region.

However, to fully realize the potential of personal and portable technologies for learning, a number of CELF research challenges must be effectively addressed. These infrastructure and research challenges include:

- How can CELF help to link computer-based and real-world experiences into augmented-reality, seamless, experiences through the use of GPS, wireless devices, sensors, and handheld or wearable mobile devices?
- How can CELF be used to successfully mediate learning across all the contexts in which it happens?
- How can personal and portable technologies provide learners with access to the full range of resources afforded by CELF, including scientific data sets and online communities of practice?
- How should Lifelong Learning Chronicles (LLCs) be developed to include information from such a wide range of experiences and using such a broad range of technologies? How should privacy be ensured and consent appropriately sought?
- How should personal and portable technologies be designed, developed and assessed to support the flexible needs of mobile learners across the boundaries of all of their living contexts?
- How should theories of learning and metacognition be adapted to recognize that learning can be distributed, transient and mobile? What scaffolding systems are necessary to support learning in these distributed learning environments?
- How can teachers' professional development exploit personal and portable technologies, and how should we enable teachers to adapt, manage, and create learning experiences that involve these technologies?
- Will the generally successful and personal relationship that users of mobile technologies form with their devices continue if they are made part of a culture of formal schooling?

Virtual Learning Environments: Virtual Resource Centers and Digital Libraries, Gaming, Simulation, and Modeling

There is a growing use of virtual learning environments such as virtual resource centers and digital libraries, games, simulations, and models for work, play, entertainment, and scientific inquiry. Their potential for learning appears to be substantial as well.

Virtual resource centers and digital libraries. Virtual resource centers and digital libraries, for example, are known to impact the learning of students and teachers who continue to re-engage with them over time because they include opportunities for interaction, knowledge-building, and autonomy.[38] In such

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[37] See http://www.birdsource.org/gbbc/

[38] Renninger, K. A., & Shumar, W. (2002). Community building with and for teachers: The Math Forum as a resource for teacher professional development. In K. A. Renninger & W. Shumar (Eds.), *Building Virtual Communities: Learning and Change in Cyberspace* (pp. 60-95). New York: Cambridge University Press.

contexts, the community of participants serves to support learners to stretch their understanding and to enable changes in their sense of possible selves[39] that differs from those available in their local school.[40] In-depth interviews with 42 teachers over a three-year period revealed that it would not be unusual for a teacher who may not think she is strong in mathematics to become a lead teacher in mathematics and technology at another school. Similarly, students working with online interactive non-routine challenge problems in mathematics have been found to strengthen and deepen their mathematical thinking.[41]

Of note in each of these contexts is the role of interacting with others as a resource for developing knowledge. For teachers, the community that emerges online is one that extends the possibilities of the local school district. On a heterogeneous site, this means not only a range of other teachers, but also tradespeople (e.g., roofers or pipe fitters who work and apply mathematics in their daily lives), mathematicians, scientists, researchers, educators, and parents from all over the world. There is a wide range of expertise and models of ways to think and talk about mathematics or science and resources that others have used effectively. In addition, the possibility of working alongside others grappling with similar issues in their classrooms, with the likelihood of finding oneself in the position of being both a learner and a supporter of others, is powerful for teachers.

A wide range of connections to others who are doing and thinking about subject content and pedagogy, coupled with the presence of interactive online services that have immediate possibilities for classroom use and/or discussion of applications to the classroom (e.g., technology-enhanced problems that fit reform practice and challenge students to stretch their understanding; question-and-answer services that enable students and/or teachers to think and talk with others about mathematics or mathematics pedagogy; an archives of like problems, already answered problems, and lesson plans), allow teachers to find and use materials that match the questions and needs that teachers bring to a virtual resource center or digital library.[42]

For students, working with content online can provide direct contact and interaction with people whose content knowledge is rich and deep—for example, others who are interested in thinking at length about a mathematics issue that their teachers or peers are not. Technology-enhanced problems provide visual representations of mathematics that are not possible in pencil-and-paper formats; they also afford the possibility of interaction that allows the student to explore a concept—moving an axis or inserting a large number, for example—to see the impact of making such a decision. Importantly, students really like this form of online mathematics, and even weaker students are likely to persevere and develop a mental model of what the problem is asking.[43]

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[39] Markus, H., & Nurius, P. (1986) Possible selves. *American Psychologist*, 41, 954-969.

[40] Shumar, W., & Renninger, K. A. (2002). On community building. In K. A. Renninger & W. Shumar (Eds.), *Building Virtual Communities: Learning and Change in Cyberspace* (pp. 1-17). New York: Cambridge University Press.

[41] Renninger, K. A., & Farra, L. (2003). Mentor-participant exchange in the Ask Dr. Math service: Design and implementation considerations. In M. Mardis (Ed.), *Digital Libraries as Complement to K-12 Teaching and Learning* (pp. 159-173). ERIC Monograph Series.

[42] Renninger, K. A., & Shumar, W. (2004). The centrality of culture and community to participant learning at and with The Math Forum. In S. Barab, R. Kling, & J. Gray (Eds.), *Designing for Virtual Communities in the Service of Learning* (pp. 181-209). New York: Cambridge University Press.

[43] Renninger, K. A., Sinclair, N., Hand, V.M., Stohl, H., Alejandre, S., & Underwood, J. (2004). Students' interest for and work with applet-enhanced word problems. *Proceedings of the International Conference of the Learning Sciences.*

Online interaction with others, such as that built into exchanges and feedback about the online problems, provides students with individualized feedback about their work, the kind of exchange in which others think with them, point them to related resources, and so on. A recent study of students working with technology-enhanced mathematics challenge problems, however, suggests that students who are best positioned to work with feedback about this type of problem online may be those who have an interest in mathematics. Although they may like working with the online non-routine challenge problems, students with less, or no, interest in mathematics need support from their teacher to seriously engage in the feedback they receive.[44]

Gaming, simulation, and modeling. Games clearly motivate users in ways that much conventional instruction, including online non-routine challenge problems, does not.[45] Some have observed[46] that game players learn implicitly in the context of playing games, and are motivated to continue learning outside of the game in order to improve their game play. Game players are motivated to continue playing out of a sense of fun and enjoyment, characteristics that are often lost in formal instruction.

Simulations and models help provide (but do not guarantee) insights into scientific concepts and phenomena.[47] Difficult abstract concepts and large data sets can be accessed in ways that are more visual, interactive, and concrete. As such, simulations and models, and the games that incorporate them, have much to offer throughout a student's learning experience. Just as simulations and computational models play an increasing role in scientific and engineering practice, they can and should play a prominent role in learning. The challenge is to lay the scientific and technical groundwork to ensure that games and simulations have a positive influence on learning, not one that is negative or distracting.

To achieve these goals, a number of Cyberinfrastructure and research challenges must be addressed, including:

- Virtual learning environments need engines, authoring tools, and other modeling tools that make it easy for students, educators and other practitioners to create interactive services, games and simulations—quickly and at low cost. The current commercial game industry is characterized by proprietary platforms and licensing restrictions that create barriers for their educational applications. NSF and other government agencies can play a role in promoting interoperability standards, and in promulgating tools, platforms, and protocols for creating and modifying games.
- An infrastructure for data collection and analysis needs to be built into virtual learning environment engines to inform the development of Lifelong Learning Chronicles (LLCs; see chapter 3). Instrumentation is lacking from commercial game engines, yet is critical for the Cyberinfrastructure in general. This infrastructure must support distributed data collection, both at home and in school, yet be secure, sensitive to privacy concerns, and tolerant of network connectivity problems in real-life educational settings.

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[44] Renninger, K. A., Boone, S., Luft, I., & Alejandre, S. (in press). Working with tPoWs (technology-rich problems): Learning in and from practice. In L. Van Zoest (Ed.), *Teachers and Researchers in the High School Mathematics Classroom.* Alexandria, VA: National Council of Teachers of Mathematics.

[45] For a study of 30,000 game players, see Yee, N. (2005, in press). The demographics, motivations and derived experiences of users of massively-multiuser online graphical environments. *PRESENCE: Teleoperators and Virtual Environments, 14*.

[46] Salen, K., & Zimmerman, E. (2003). *Rules of play: Game design fundamentals*. Cambridge, MA: MIT Press.

[47] DiSessa, A. (2000). *Changing minds: computers, learning, and literacy*. Cambridge, MA: MIT Press; Frederiksen, J. R., White, B.Y., & Gutwill, J. (1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching, 36*(7), 806-836.

- Cyberinfrastructure is needed to coordinate between virtual and real activities and resources. For example, learners need to be able to move seamlessly between game scenarios, Web-based resources relating to the concepts in the game scenarios, and online discussion groups and communities of learners employing these scenarios. Learner profiles and histories need to be portable between games and worlds, and through experiences spanning the learner's educational career, so that the learner need not start afresh with each new game-based learning experience.

- We need tools and infrastructure that help bridge the gap between models and simulations used in scientific and engineering practice and those used in education. Models used by practicing engineers and scientists tend to be highly detailed and require significant expertise to understand. However, if properly abstracted, simplified, annotated, and augmented, they can be transformed into learning resources as well.[48]

- Cyberinfrastructure must address a range of digital divide concerns, including low-cost delivery options and interfaces that support all learners to access Web content, including those with diverse linguistic abilities and those with disabilities who need assistance in perceiving, understanding, navigating, and interacting with Web sites and applications.[49] Novel interface modalities and participation structures are needed to support pre-K, primary, and secondary learners, as well as adult learners across the life span.

Although some evaluations of learning in virtual environments have been performed[50,51,52,53] and others have been proposed,[54] more empirical research needs to be done, particularly of modern highly immersive games and learning environments. The field of K-12 learning in virtual environments may also benefit from lessons learned in the thriving field of simulated training environments, including those of the military, and in the convergence of work in medicine and virtual reality.[55]

- Multiple researchers[56] have observed that good games motivate learners to seek knowledge outside of the game in order to improve their performance within the game. Research in curriculum design and evaluation is needed to establish design principles for adapting curricula—to include interactive services such as online non-routine challenge problems, Web resources, integration of games and simulations—and to deepen our understanding of how to exploit the use of CELF to enable learners to work effectively with game-based and non-game-based materials.

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48 For one example in the atmospheric and environmental sciences, see Edelson, D.C., Gordin, D.N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences*, 8(3&4), 391-450. For a molecular simulation engine designed specifically to support pre-college learning, see the Concord Consortium's *Molecular Workbench* (http://workbench.concord.org/), and other contributions of Concord's "Modeling across the curriculum project" (http://mac.concord.org/).

49 See the Web Accessibility Initiative of the World Wide Web Consortium (http://www.w3.org/WAI/).

50 White, B. (1993). Thinkertools: Causal models, conceptual change, and science education. *Cognition and Instruction*, 10, 1–100.

51 Salzman, M. C., Dede, C., Loftin, B., & Chen, J. (1999). A Model for Understanding How Virtual Reality Aids Complex Conceptual Learning. *Presence: Teleoperators and Virtual Environments* 8 (3), 293-316.

52 Dev, P., Montgomery, K., Senger, S., Heinrichs, W.L., Srivastava, S., & Waldron, K. (2002). Simulated medical learning environments on the Internet. *J. Am. Med. Inform. Assoc.*, 9(5):437-447.

53 Virvou, M. Katsionis, G., & Manos, K. (2005). Combining software games with education: Evaluation of its educational effectiveness. *Educational Technology & Society* 8 (2), 54-65.

54 Winn, W. Learning in Virtual Environments. http://www.hitl.washington.edu/projects/learnve/

55 http://www.nextmed.com/mmvr_virtual_reality.html

56 For example, Gee, J. (2003). *What Video Games Have to Teach Us about Learning and Literacy*. New York: Palgrave Macmillan.

- Studies must be conducted to assess the roles of motivation in online services and game-based learning that require self-regulation. Should design be undertaken such that learners are motivated to learn the concepts underlying a game, for example, as opposed to simply learning tricks for playing the game?[57] This will require enhancement of our basic understanding of motivation and engagement at the neurobiological, cognitive, and sociocultural levels.
- We need comparative analyses of learning where conjectured key features of interactive online services, gaming, and simulation environments are systematically removed, added, or altered in order to assess their impacts in relation to the strength and needs of learners. This requires the flexible, reconfigurable virtual environment engines alluded to above, as well as the instrumentation infrastructure to monitor, measure, and summarize learner performance using multiple media data streams and modalities, such as physiological sensing,[58] not only traditional input device data. It also requires that support be provided to ensure effective use by learners, teachers and parents.
- We need a better understanding of the important role of virtual-environment-oriented "learning communities." There is a common misconception that collaboration does not arise in connection with such virtual environments unless it is itself a multi-player world. Conversely, the effectiveness of virtual world online communities in promoting learning offers valuable lessons in how self-organized online communities can promote learning and the sharing of knowledge.
- We need studies and theoretical frameworks that help us to understand and critically evaluate the role of fidelity and immersiveness in virtual-world learning experiences, and in enhancing human task performances. In certain contexts, or for particular purposes, 'less' can be 'more.'
- We need studies to assess the potential negative effects of game-oriented learning. These include negative transfer from faulty simulation models, reinforcement of gender biases, the "rich-get-richer" effects in social networks and learning communities [the modern-day equivalent of what Merton (1968)[59] called "The Matthew Effect"—see also Barabasi (2002)][60] for these "highly interlinked hub" effects in networks], emphasizing action/"twitch" effects over reflection, and overemphasis of "eye candy" and other distracting details to the detriment of substantive learning.
- We need research projects that will investigate the use of models and simulations to convey highly abstract conceptual ideas that are suited to the developmental level of learners.

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[57] Prensky, M. (2000). *Digital game-based learning*. New York: McGraw-Hill. Cordova & Lepper, 1992.

[58] Allanson, J. (2002). Electrophysiologically interactive computer systems. *IEEE Computer, 35*, 51-59; Picard, R.W. (2000). Towards computers that recognize and respond to user emotions. *IBM Systems Journal, 39* (3–4), 705–719; Predinger, H., Mori, J., & Ishizuka, M. (2005), Using human physiology to evaluate subtle expressivity of a virtual quizmaster in a mathematical game. *International Journal of Human-Computer Studies, 62*, 231-245.

[59] Merton, R. K. (1968). The Matthew Effect in science: The reward and communication systems of science are considered. *Science*, 159(3810), pp. 56-63.

[60] Barabasi, A. (2002). *Linked: The new science of networks.* New York: Perseus.

- We need to study the sociocultural differences in preferred gaming metaphors, graphical worlds, and avatars for different learner groups, and investigate how to create game-based media that are sensitive to, and even can exploit, these factors without reinforcing negative stereotypes. Virtual reality environments for research enable nuanced social science research questions[61] to be addressed concerning such learning-relevant topics as identity presentation and interactional consequences (e.g., when a young white male can be represented as an adult black man—how is stereotype threat experienced?).
- Games and simulations raise new professional development issues for teachers. The new literacies involved in such media need to be developed for teachers, as well as methods that enable them to adapt, manage, and create virtual-world learning experiences and curricula for their purposes (see chapter 3).
- The role of scaffolding in virtual learning environments needs to be carefully studied and developed.[62] For example, games provide a range of scaffolding techniques, including simplified game modes ("fishtanks" and "sandboxes") with interaction that provides players with immediate feedback on their actions. Scaffolding can be embodied in characters, such as buddies and mentors, that are "embodied conversational agents" that engage in dialogic support for learners.[63] These techniques should complement, and not duplicate, the kinds of scaffolding common in intelligent tutoring systems. Moreover, the role of scaffolding changes when learners become self-motivated to improve their own skills.
- The roles of narrative, stories, goal-based scenarios, and vignettes in virtual learning environments need to be properly understood. Story lines can make learning experiences more memorable and salient, but can also reduce the scope of learner control and can make it more difficult to introduce repetitive practice where it is needed and valuable.

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[61] Blascovich, J., Loomis, J., Beall, A., Swinth, K., Hoyt, C., & Bailenson, J.N. (2002). Immersive virtual environment technology as a methodological tool for social psychology. *Psychological Inquiry, 13*, 103-124.

[62] Pea, R. D. (2004). The social and technological dimensions of "scaffolding" and related theoretical concepts for learning, education and human activity. *Journal of the Learning Sciences, 13*(3), 423-451.

[63] Maldonado, H., Roselyn Lee, J., Brave, S., Nass, C., Nakajima, H., Yamada, R., Iwamura, K., & Morishima, Y. (2005). We learn better together: Enhancing eLearning with emotional characters. *Proceedings of Computer Supported Collaborative Learning 2005.* Mahwah, NJ: Erlbaum.

3. Lifelong Learning Chronicles:

How Do We Develop a Rich Qualitative and Quantitative Record of Learning Over Time in a Way that Informs a Multitude of Stakeholders?

Educational innovations and improvements are greatly hampered by the lack of sufficient quantitative data to properly assess their effectiveness and optimize their use. This is the motivation for a major thrust within the educational Cyberinfrastructure initiative to create a digital "Lifelong Learning Chronicle" (LLC) for each learner to collect and track the breadth and depth of that learner's experiences over his or her lifetime, and usefully indexes them for both personal reflective learning and certification purposes.

The use of digital learning portfolios for personal ownership by learners has been a recurrent concept in recent history. It was intimated in Vannevar Bush's pioneering 1945 "As We May Think" essay through his imagined digital notebooks for the scientist, which portended today's hypermedia systems and the World Wide Web. Massive reductions in the size and cost of digital storage, now less than the cost of paper, make progress on this issue more tractable. Similarly, recent advances in machine learning and vision provide support for more robust person and object recognition, speech recognition, purposeful data-mining, and so on. In sum, the proposed LLC is an application of the frontiers of computing research—as described in, for example, the "Personal Memex" and "World Memex" (Jim Gray's 1998 Turing Award Speech),[64] Gordon Bell's work on MyLifeBits,[65] and the UK "Memories for Life" Grand Challenge Project[66]—to learning and education.

LLCs can offer rich and compelling information to a wide variety of stakeholders. For example, individual learners would have the data they need to make informed decisions about their own learning—what knowledge they need to study, what learning resources are available that best align with their interests and learning style (instead of the one-size-fits-all textbook), what metacognitive skills could be improved, and what strengths and weaknesses they have that may influence future academic and employment choices. Learners will no longer have to take a single-shot, high-stakes assessment, but instead can benefit from continuous embedded assessments that provide both multiple opportunities to demonstrate their strengths and more rapid and accurate feedback to help in remediating their weaknesses.

However, the benefits of an LLC do not end with the learner—teachers, parents, administrators, researchers, policy makers, and society in general can all benefit from such a rich record. *Teachers* can guide their students' learning more effectively, professional development can be enhanced, and ultimately teaching can become more rewarding. *Parents* can also help their children learn, monitor their ongoing progress and make informed decisions about how to support their education. *Administrators* will have information for use in allocating resources appropriately so they can guide, support and reward teachers. *Researchers* can use LLCs to more deeply understand the processes involved in learning, particularly with respect to the new educational possibilities that Cyberinfrastructure affords. As a result, they will be able

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[64] Gray, J. (2000). *What Next? A Few Remaining Problems in Information Technology,* SIGMOD Conference 1999, ACM Turing Award Lecture, Video. ACM SIGMOD Digital Symposium Collection, 2(2).

[65] http://cimic.rutgers.edu/~sigmod05/SIGMODkeynote.htm; also see http://research.microsoft.com/CARPE2004/ for *CARPE 2004: The First ACM Workshop on Continuous Archival and Retrieval of Personal Experiences.*

[66] http://www.memoriesforlife.org/

to develop better Cyberinfrastructure learning technologies. *Policy makers* will have the opportunity to judge the effectiveness of new policies more quickly and accurately and respond accordingly. *Workforce and training departments* would be better able to account for workers' prior learning (including in informal settings) and develop individualized training. *Industry* would better understand what is required of the technologies when applied to the purposes of learning and education, and develop services that would better support them. Combining all these benefits, the better-educated and more adaptive workforce that will result from the use of LLCs should increase economic competitiveness.

For all these stakeholders, a major benefit of the continuous learner data collection is the possibility of much more rapid, informative, and accurate feedback and responsiveness than is possible with today's practices of occasional high-stakes and summative tests administered by teachers, instructors, and testing agencies during the school year. Data collection can go beyond traditional measures of domain content acquisition to include records of such factors as the processes learners have used in solving problems, information about whether learners are asking for help appropriately, and the way that learners may collaborate, cooperate and argue with each other. Faster cycles of feedback not only would foster better instructional decision making, but research in learning technology that is better focused on effective design and appropriate uses of that technology as well.

More generally, CELF should improve partnerships among these key education stakeholders and enable the tighter coupling of research, educational design, classroom practice and assessment, and industry's technical developments.[67] Among other things, this would have implications for how NSF-supported learning sciences research and development is conducted, including that of NSF's Science of Learning Centers program. Currently, most research projects are very loosely coupled and results rarely are cumulative in the knowledge that they produce. Too often learning technology research projects are far removed from classroom practice and its exigencies. The Cyberinfrastructure provides the opportunity for these projects and communities to work together more effectively.

A dramatic characterization of how the Cyberinfrastructure could radically transform educational research and its connection to practice is captured by the phrase contributed by workshop attendees: "Make America one big research school." Some Cyberinfrastructure tools will capture fine-grained information on how students perform, and others will enable us to do sense-making by mining these data in order to address important questions related to assessment and learning sciences research. Distributed databases (from classrooms and other venues across the country) could aggregate these data on a continuing basis, and the learning research community could tap the data to address important questions on learning, cognition, and design.

The technical viability—as well as research challenges—of a digital LLC should be evident. Cyberinfrastructure technology developments will make it possible to store, search, and access records from LLCs. There has been continued exponential growth from 1990 to 2003 in hardware capabilities, including processor speed by a factor of 400, memory by a factor of 120, wireless speed by a factor of 18, and fiber channel bandwidth by a factor of 10,000 (Atkins, 2003, see footnote 2). In five to seven years,

[67] On these points, see: Pea, R., Wulf, W., Elliot, S.W., & Darling, M. (2003, August). (Eds.). *Planning for two transformations in education and learning technology* (Committee on Improving Learning with Information Technology). Washington, DC: National Academy Press.

mobile "phones" will have gigahertz processors and a gigabyte of memory. And as one UK report on "memories for life" notes, "The digital archive of even one person in the year 2019 is likely to consist of petabytes of linked images, documents and audio; the potential for extracting useful knowledge from this archive is stupendous, and only limited by our imagination."[68]

The data-mining opportunities and challenges for LLCs are evident in considering even a basic data model. Consider the situation if and when each learner has a wireless handheld or laptop computer, and learning environments enable teachers and instructors to sustain regular learning conversations with their students that are technology-mediated in some measure. We see this trend emerging now with "classroom response and communication systems" in which teachers can pose questions (multiple choice and other designs) to which all their students can immediately respond, either anonymously or with identification. These responses help teachers quickly gauge the students' conceptual understanding. Meanwhile, aggregate displays of student responses become visually available to the whole class through the teachers' projected computer display, enabling students to see the views of their peers. Archiving interactions, furthermore, permits study of the exchanges, providing a basis for assessment and feedback to the learner and the teacher, as well as needed information for service and/or gaming, simulation, and model refinement and development.[69]

For the 180 school days, each of 55 million U.S. K-12 students has about six periods of 50 minutes per class. If the teacher provides an occasion for each student to provide a response to his or her queries only once every five minutes of classroom time on such a technology platform, each student would have more than 10,000 such learning transactions in an academic year. This base model alone would generate 500 billion data points annually for U.S. K-12 students—and we are not yet even considering the need to capture each learner's background or profile data and relate it to this emerging data stream or to other data streams (such as interaction patterns with software systems during individual or group learning, audio or video data, and so forth; see below).

The LLC that the Cyberinfrastructure enables will extend beyond the walls of the classroom to include learner interaction data from a wide variety of information and communication technologies and media data streams. These include educational, performance, and entertainment technologies software (virtual laboratories, modeling tools, intelligent tutors, online assessments, and games), chat rooms, discussion boards, interactions with science museum exhibits, GPS-enabled cellular phones, and phone and grid conferences. This will require storing recordings of learner activities with both standard and novel recording techniques that capture *synchronized data streams.* The use of audio, video, scanners (e.g., for paper homework and tests), eye tracking, emotion sensing (e.g., galvanic skin response, or GSR), location/ proximity sensing (e.g., GPS), and brain imaging has tempting potential for deepening the scientific understanding of learners and how learner profiles and contextual factors contribute to learning processes and outcomes.

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[68] Fitzgibbon, A., & Reiter, E. (2003). *Memories for life: Managing information over a human lifetime.* Paper presented at UKCRC (UK Computing Research Committee's) Grand Challenges in Computing workshop. (http://www.memoriesforlife.org/documents.php)

[69] Renninger, K. A., and Shumar, W. (2004). The centrality of culture and community to participant learning at and with The Math Forum. In S. Barab, R. Kling, & J. Gray (Eds.), *Designing for Virtual Communities in the Service of Learning* (pp. 181-209). New York: Cambridge University Press.

Cyberinfrastructure and research challenges include:

- Analysis and visualization methods for distilling meaningful assessments from LLC data must be developed and presented in a form that learners, teachers, and other stakeholders can use. New methodologies of "visual analytics" will be needed for the analysis of enormous, dynamic, and complex information streams that consist of structured and unstructured text documents, measurements, images, and video. Significant human-computer interaction research will be required to best meet the needs of the various stakeholders. Stakeholders ought to be able to "drill down" into these assessments to see the justification for them in terms of learner performance. Analyses should be auditable, particularly when they have an impact on decision making, including college admissions and school-system performance assessments. These tools must be designed to give high priority to protecting the privacy and security of the data and users.
- There are many challenges and opportunities in collecting data for the LLC once it is understood that so much of learning occurs outside formal schooling. For example, how should educational games be instrumented to collect data, or children's interaction with mobile technologies be logged as they participate in field trips and visit museums, libraries, and other events? This information can provide for a deeper understanding of the way that informal learning supports formal schooling, but the technological and societal issues associated with its collection, analysis, and interpretation are more complex.
- The problems of protecting privacy and securing appropriate access permissions will need to be addressed. Fundamental computer science research will be needed to address such challenges (e.g., face tracking to anonymize video, more automated parsing and semantic coding of speech and video). Social scientists will also need to address privacy and security issues from a policy perspective.
- How should *learning environment design* be re-conceptualized? It is inevitable that unforeseen data patterns will emerge from the multiple synchronized data streams of learners and groups, given the present state of "data poverty," when we consider how little we currently capture about learners and their conditions of learning. Identification of emergent data patterns from these data streams could be defined as new "sensed quantities" in a classroom—properties of the classroom as a learning system that are changing over time. Such measures could be taken and used as *inputs* that would serve as triggers for dynamically changing the affordances of the learning environment. In short, we see great potential for using wireless sensor networks for gauging the dimensions of learning, and the design of learner-learner-teacher-media interactions as a challenging and exciting area of inquiry for CELF to tackle.

- Identify relevant variables for analysis. What, for example, "counts" as scientific or mathematical thinking or literacy, and how can it be assessed online?
- Develop methods for comparative analysis of learner performance across LLC data nationwide. This is a major challenge for distributed computing, exacerbated by the fact that the necessary data are likely to be distributed in heterogeneous databases that may be intermittently disconnected from the Internet.
- Psychometric validation of LLC-based assessments is needed so they can be compared with conventional assessments, and complement and ultimately supplant them.
- How should the multiple data streams be synchronized (e.g., audio, video, scanners, eye tracking, emotion sensing, location/proximity sensing and brain imaging) to allow the rich descriptions that qualitative information provides to be coupled with precise quantitative accounts?
- Preservation and migration of data must be addressed. LLCs will have a lifetime that far exceeds the specific technologies used to store them. Moreover, as needs and capabilities change, LLC data formats and protocols are bound to change as well. Preservation and maintenance of LLC data will be a continual problem, and will require innovative solutions.

4. Teaching Through the Cyberinfrastructure:

What Are the New Images of Teaching Afforded by the Cyberinfrastructure?

While the Internet has clearly influenced the opportunities available to a number of teachers, the working environment for many who have yet to connect to it may be unsatisfying professionally and lacking in intellectually enriching experiences, pathways for professional advancement, and sufficient resources for teaching their classes. Poor performance nationally and locally has led to increased demands for accountability and the record-keeping and testing that goes along with this. As these demands increase, the inadequate allotments of time and resources for professional development are further constrained, while new requirements such as technological competence and literacy are added.

The Cyberinfrastructure for education presents the opportunity to address many of the existing challenges. It will also extend already documented possibilities for teachers' professional development, while introducing new contexts demanding new modes of teaching and assessment. It can enable teachers to further develop their own knowledge and skills in the context of supporting them to work with these.[70] In the K-12 arena, numerous studies and reports have documented the shortage of qualified teachers, related to poor preparation in pedagogical content knowledge and large turnover in the profession.

Consider the following scenario depicting an enriched classroom environment using Cyberinfrastructure:

Sherry is a tenth-grade science teacher. In preparing an earth sciences class, she downloads recent seismological data and incorporates them into a game-like, inquiry-based classroom activity. She feels a bit unsure about how to best structure the student groups and how to design her class activity, so she logs into her online professional development environment where her mentors provide advice and assistance. Her refined activity then becomes available to other teachers for use and adaptation. Along the way, Sherry learns more about the physics of shock wave propagation. Indeed, she learns to use a software tool that models this phenomenon.

In class, Sherry walks about the room, offering help and advice as students work through the activities. Because of the extended nature of the activity, students continue working collaboratively on the project at home. The environment includes a simulated scientist agent who can offer advice. As part of the activity, they use sensors connected to handheld devices to explore and collect vibration data in different physical environments. One student continues working on the problem during his after-school technology club. Other students in the club become engaged and suggest other resources for solving the problem.

Sherry, meanwhile, can assess students' progress and learning activity by accessing tools that visually display real-time analyses of their performance, attitudes, and the nature of their collaborative activity. She can consult her online assessment mentor to help her interpret these dynamically generated analyses, and offer tailored and developmentally appropriate feedback. Report generation software helps her prepare reports for parents and district administrators. These analyses can also help Sherry reflect on the quality of the instructional activity, student learning, and ways to implement improvements.

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[70] Existing large-scale commercial efforts using Cyberinfrastructure to serve these needs with digital video and media-rich interactive learning resources and online community include Teachscape and LessonLab.

As described above, CELF can change the landscape by supporting student-directed inquiry using services and activities that provide scaffolds and generate Lifelong Learning Chronicles (LLCs) that model and analyze a student's performance and learning activities. For teachers, the Cyberinfrastructure provides a means for connecting their students to new virtual communities of practice and, through this, expanding the teaching and mentoring resources available to students. Cyberinfrastructure can also change the nature of the classroom, enabling early pre-service access to students and classrooms, supporting them to target and develop particular competencies such as analyzing students' efforts—for example, in the process of mentoring elementary students who are encountering online problems with their work—and connecting them to the range of possible ways to access other professional roles and activities.

In turn, these changes will introduce the need for new competencies in teaching. The availability of richer performance data will require that teachers integrate new skills in technology use, interpretation of student performance based on a wide range of data, and designing interventions in order to yield the desired improvements to education. As students can have more direct access online to current and high-quality content and engaging experiences, the role of the classroom teacher as facilitator becomes even more important, helping students manage their online learning relationships and activities, articulate and share their learning, and assess their progress.

Online communities of learning have the potential to strongly support professional development. Early research suggests that participation in these communities supports a changed sense of identity and possibility because of their availability, comprehensiveness, and user-centered control over participation; their relative anonymity; the ease of movement within and between communities and roles; and the strength of engagement that comes from interest and access to strong community members.[71] The ability to easily try out roles, from lurking participant to author or program facilitator, provides motivation and opportunity for teachers to reflect on their professional activity, receive feedback and affirmation, and pursue advancement.[72]

A "teacher" for every student and every student a teacher. Interestingly enough, this has been previously identified as a Grand Research Challenge for Information Systems (*Grand Research Challenges in Information Systems*, Computing Research Association, September 2003, http://www.cra.org/reports/gc.systems.pdf). There are multiple emerging forms of providing more Socratic tutoring and interactive and individualized support more cost-effectively. These include interactive services (e.g., Ask Dr. Math, TeacherToTeacher, or Problems of the Week, on The Math Forum site[73]), educational games, and intelligent tutors. There is also the opportunity to better tap the distributed expertise that is available in the learner population to enhance the learning that goes on at the system level. That is, any student can also serve as a teacher to other students and, as CELF develops, it will be easier to recognize which learners could serve as teaching resources for which of the other learners, pending their reputation authentication and availability and mechanisms for brokering such learning interchanges effectively. CELF could change the opportunities for a wider range of people to have more ways of playing a teaching role, bringing their expertise to students as education breaks out of the normal classroom structure. We can foresee a different process for

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[71] See discussions in Barab, S., Kling, R., & Gray, J. (2004). (Eds.), *Designing for Virtual Communities in the Service of Learning.* New York: Cambridge University Press; and Shumar, W., & Renninger, K. A. (2002). On community building. In K. A. Renninger & W. Shumar (Eds.), *Building Virtual Communities: Learning and Change in Cyberspace* (pp. 1-17). New York: Cambridge University Press.

[72] Renninger, K. A., & Shumar, W. (2004). The centrality of culture and community to participant learning at and with The Math Forum. In S. Barab, R. Kling, & J. Gray (Eds.), *Designing for Virtual Communities in the Service of Learning* (pp. 181-209). New York: Cambridge University Press.

[73] http://www.mathforum.org

cultivating interest in serving in teaching roles and in becoming a teacher, including building interest over a longer cycle of continuous connection in mentoring activities, or transitioning from other jobs later in the life course.

In the higher education realm, new instructors, who often have little formal preparation as teachers, can become part of online communities where they can consult mentors, other new teachers and more experienced teachers, tradespeople using their discipline in the field, and others to find high-quality learning resources for their courses.

This vision of teaching and teachers in the Cyberinfrastructure environment raises a number of research challenges. The research on learning and teaching in these different types of online and hybrid communities is very preliminary, and there is much to be understood. It is critical that strong models and communities of learners be developed to support teacher learning so that CELF supports the improvement of education rather than competing with it. This research must lead to design requirements and criteria for assessment that are used to develop platforms for collaboration and community development on which educational program leaders can participate and refine their curricula and pedagogies.

Cyberinfrastructure teaching and research challenges include:

- Developing models of effective mentoring and approaches for supporting the development of identity-changed learning in online professional development environments. Addressing issues of incentives, release time, recognition, and rewards for participation in such environments (see chapter 5).
- Developing models for supporting sustainable, productive online communities (see chapter 5).
- Supporting the meaningful integration of Cyberinfrastructure skills and resources (e.g., networked instruments, data sets, visualization, and modeling software) into formal learning environments. Providing the means for harnessing the potential of Cyberinfrastructure resources for teachers to engage in developing and deepening subject content knowledge and pedagogical content knowledge.[74]
- Understanding teaching as a complex work environment. This includes providing effective tools, mentors, and support in teaching environments with integrated student learning, performance, assessment, and feedback (see section on Lifelong Learning Chronicles, chapter 3).
- Developing robust models of teaching and curriculum development that prepare all kinds of students to work in the Cyberinfrastructure world, including models for designing interdisciplinary and collaborative curricula.
- Fostering teaching across boundaries: supporting students' transitions in learning from virtual learning environments with formal and non-formal learning environments. Developing standards supporting the transparent portability of information about user capabilities across contexts. Developing social and technical theory that supports seamless navigation between life spheres.

[74] Davis, E., & Krajcik, J. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher, 34*(3), 3-14.

5. Communities of Learners:

How Can the Cyberinfrastructure Support and Transform Communities of Learners?

The virtual world has expanded the communities of learning in which students and teachers can participate and the roles that virtual environments can play in the educational system. Even more, communities of learning are situated in a context of social networking that has already been and will continue to be transformed by Cyberinfrastructure. In the virtual world, social networking functions (such as face books and recommender systems)[75] can enable learners to aggregate into communities of interest and evolve into communities of learning or practice.[76] We need to understand the formation of these communities and ways to facilitate the contribution of cybersocial networking to the learning and engagement of students and teachers. Additionally, social capital influences who participates and the focus of community activity, which leads to various learning outcomes for different types of learners and groups.[77]

Virtual communities of learning also offer the promise of bridging the worlds of work and education. Cyberinfrastructure will make it possible for students in school settings to be more directly engaged with life beyond the classroom, and to observe and interact with communities of professionals and others who develop products and results that matter, both within and outside of their communities. Additionally, experience with virtual communities of learning directly prepares students for working in such environments outside of school-based education. Much work needs to be done to manage layers of participation that enable students and others to participate, at levels appropriate to their interest and competencies, in ways that do not intrude on the work of the others yet make their results and activity accessible as appropriate.

Virtual communities of learning can help address many of the issues raised above about the need to retain qualified and talented teachers and support them in their professional practice. They can provide personal support as well as access to professionally interesting conversations and resources; connections to practicing scientists and education researchers; and more opportunities for advancement than the local context often can offer.

CELF research challenges include:

- Managing the need for large-scale, robust production systems upon which practitioners can rely and researchers can do research, coupled with the ongoing need for innovative experiments.
- Developing shared standards and specifications to enable the collection and analysis of data about communities of learning.
- Understanding and planning for educating teacher practitioners to use Cyberinfrastructure for learning collaboratively and across groups.

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[75] See, for example, Recker, M., Walker, A., & Lawless, K. (2003). What do you recommend? Implementation and analyses of collaborative filtering of Web resources for education. *Instructional Science, 31(4/5)*, 229-31.

[76] Renninger, K. A., & Shumar, W. (2002). Community building with and for teachers: The Math Forum as a resource for teacher professional development. In K. A. Renninger & W. Shumar (Eds.), *Building Virtual Communities: Learning and Change in Cyberspace* (pp. 60-95). New York: Cambridge University Press.

[77] Castells, M. (1996). *The rise of the network society*. Oxford and Malden, MA: Blackwell.

- Understanding the affordances of the virtual context for individuals and groups to develop multiple competencies and various senses of belonging that they and others can manage to construct, and adapt the learning environments to their needs.
- Understanding how social capital influences the participation of different types of learners and, in turn, how various forms of participation impact learning.
- Identifying and learning to assess criteria for engagement and success within communities of learning. Integrating across different forms of assessment data, such as interviews and observation, discourse and conversation analysis, log analysis, and performance evaluations (see LLCs, chapter 3).
- Developing effective community feedback mechanisms for "reading" member engagement and perspectives[78] and facilitating various forms of decision making.
- Understanding how access, availability, and ubiquity affect the development of Communities of Learners enabled by CELF.
- Understanding how pedagogical content knowledge[79] and related principles should influence the design of infrastructures to support communities of learning.
- Understanding how to support cross-project collaboration and fertilization. Understanding how Cyberinfrastructure can bridge projects both within and across traditional disciplines. Understanding how projects move from pilots to large-scale efforts and from grant-funded to sustainable.
- Understanding the *global* nature of Cyberinfrastructure. Although the Internet and much of industry are already internationally oriented, education in the United States is remarkably parochial. Cyberinfrastructure can help bridge learners across countries (pilots, and small-scale individual efforts) and make it possible (time zones notwithstanding) for class projects to consist of team members worldwide, and to bring in experts from around the world.

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[78] Kim, A. J. (2000). *Community building on the web.* Berkeley, CA: Peachpit Press.

[79] Knowledge about how students develop knowledge that is used to guide effective instruction, see Shulman, L. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15* (2), 4-14.

6. Educational Policy and the Cyberinfrastructure:

What Changes in Processes, Policies, and Support Are Necessary To Achieve Those Educational Experiences?

This report highlights the unique opportunities and challenges that the Cyberinfrastructure presents in promoting innovation and reform in education, learning, and research. These recommendations complement and extend the recommendations in the original Atkins report (Atkins et al., 2003). That report tends to focus on engineering and the physical sciences.[80] To help ensure that the Cyberinfrastructure is created so that it meets the distinctive needs of education, learning, and affiliated social sciences research, we have emphasized this focus by coining the acronym CELF to represent the *Cyberinfrastructure for Education and Learning for the Future*. The CELF initiative must assume these challenges in order for the Cyberinfrastructure initiative to have a significant impact on education and learning in the United States.

As we have argued, establishing CELF will involve far more than making scientific data sets available online. It should provide the means for ubiquitous collection and utilization of learning-related data, in a manner that respects privacy and control concerns. It should provide tools and resources that enable learners at all levels, as well as teachers and those serving educative roles, to exploit the potential of the Cyberinfrastructure in equitable and productive ways. CELF should provide access to science and engineering resources, but in a form that learners and educators can effectively use in meaningful and tailored ways. New forms of professional development are required to enable educators to contribute to and make effective use of this Cyberinfrastructure.

Without a concerted and focused effort, the vision of CELF as a meaningful educational implement will not happen on its own. Risks include: 1) isolating education and learning from a socio-technological revolution that has already fundamentally altered the scientific process and has great potential benefits in this realm; 2) depriving learners at all levels from engaging with rich, motivating and tailored learning experiences that prepare them for work in an information economy; 3) bypassing a major chance at attracting new talent to the community of teaching professionals; 4) missing an opportunity for building balanced, continuous, and context-sensitive assessments; 5) accumulating fragmented, disconnected, incoherent data sets that cannot be shared for the purposes of informing both stakeholders and education researchers; and 6) adopting a narrow focus on analyzing and interpreting only data that are easy to collect.

Efforts to develop standards and code-sharing would address some risks. Assuming that the very difficult privacy and security issues can be addressed, then use of more sophisticated data collection methods (e.g., video, eye tracking, physiological sensing, brain imaging, automatic transcription and coding of verbal data) can also help address some of these risks. However, even with the development of standards, methods are needed to combine legacy and contemporary databases from the various sources in which they reside, such as school districts, game systems, classroom computers, and learners' personal computing and mobile devices such as cellular phones.

[80] Examples of data from that report included "the outputs of all major observatories and astronomical satellites, satellite and land-based weather data, three-dimensional images of anthropologically important objects" (p.10).

If these needs are not addressed, Cyberinfrastructure research will have a minimal impact on educational practice. CELF needs to improve learning for all learners and not just the few. Research must address the fundamental requirement that this infrastructure will enable more inclusive and accessible education. Moreover, it is unlikely that the private sector will fill the gap, given that the current Cyberinfrastructure involves a multitude of incompatible protocols and standards, with little attention to interoperable instrumentation.

Consequently, policy changes are required both to fully implement educational Cyberinfrastructure and to properly exploit it. The following are some of the areas where educational Cyberinfrastructure has policy implications. Some of these policy recommendations are also made in the Final Report of the NSF SBE-CISE Workshop on Cyberinfrastructure and the Social Sciences.[81]

Privacy, Security, and Integrity

One clear example of demands on Cyberinfrastructure, raised particularly with regard to the handling of human data (as opposed to, say, astronomical data), is *privacy*. Under most conditions of use, data on human subjects and student classroom performance must be anonymized for scientific or public use. There are significant challenges for anonymization, and a community of data privacy and privacy technology researchers has emerged. Further challenges follow from the fact that different stakeholders may have different access needs for data about student or classroom performance. For instance, we may wish to provide students and their parents with full access to their own data; teachers with full access to data on students currently in their classes, but only summary access to their current students' past performance; and school community members, administrations and researchers with only certain kinds of summary information.

The data collected using CELF's capabilities could have a huge impact on educational decision making.[82] Consequently, the data must be protected from unauthorized access, tampering and modification. Instances of unauthorized access to student records are increasingly common and are liable to worsen if appropriate precautions are not taken.

Preserving and Safeguarding Data

Educational Cyberinfrastructure will collect and store huge amounts of data about learner performance. In order to fully reap the benefits of these data, they must be stored and maintained over a long period of time. This requires institutional commitments to maintain these data sets. Moreover, steps must be taken to maintain the integrity of data once they are collected. The data collection process must have sufficient redundancy and safeguards in case of hardware malfunction or operator error. Even seemingly innocuous actions such as software upgrades could cause data sets to be overwritten and lost.

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[81] "Final Report: NSF SBE-CISE Workshop on Cyberinfrastructure and the Social Sciences", F. Berman and H. Brady, available at www.sdsc.edu/sbe/.

[82] For a report on New York City's citywide implementation of the Grow Report, a web-based data-driven decision making and instructional resource available to teachers, administrators and parents for all students in grades 3 through 8 (roughly 450,000 children), see Light, D., Honey, M., Heinze, C., Brunner, C., Wexler, D., Mandinach, E., & Fasca, C. (2005). *Linking Data and Learning: The Grow Network Study.* New York: Center for Children and Technology, (Downloaded July 6, 2005 from http://www2.edc.org/CCT/publications_report_summary.asp?numPubId=192).

Utilization

The educational Cyberinfrastructure of CELF will be beneficial only if it is well utilized. Data must be collected and saved, and not discarded. Educational technologists can strive to make educational Cyberinfrastructure as easy to use as possible, but maintaining it still requires commitment at all levels. Otherwise data are likely to be fragmentary and easily lost. Where the Cyberinfrastructure requires new types of data to be collected, such as video recordings and self-assessment instruments, policies must be in place to ensure compliance. These may be of less concern for government-funded research projects in which researchers are available to ensure compliance, but are critical as educational institutions move to adopt CELF for their own uses in mission-critical applications.

Equity of Access and Ability to Use the System

Equity issues must remain a central concern in the Cyberinfrastructure R&D agenda. Currently, students do not have equal access to high-quality instructional resources, nor do they have equal access to highly qualified teachers, particularly for higher-level science and mathematics courses. With the increasing diversity of native languages in the nation's schools and workplaces, the challenges of meeting multilingual needs are an important aspect of this access problem. Ensuring that materials are designed to address the learning challenges of underserved populations and communities is a national imperative.

Ownership

In order for educational Cyberinfrastructure to make the transition into widespread use, issues of ownership and control must be kept in mind. First of all, learners and parents should have rights to control who has access to data that are collected about them. Yet it is ultimately the educational institutions that are responsible for ensuring that the data are properly collected and maintained.

Educating the Public About Policies

The educational processes envisioned by CELF and the scenarios we have characterized require the involvement and concurrence of the public at large. The public needs to be informed of the potential benefits of the new technologies and methods, and of the protections and safeguards built in to ensure integrity and proper use. Public involvement will be required to set priorities for the use of CELF, and public support will be necessary for its proper implementation. Above all, we must make sure that there is public support for learners acquiring the types of knowledge and skills that CELF promotes and measures.

Evidence-Based Assessment and Decision Making

CELF will make possible new methods for assessing the performance of learners, teachers, schools, and school districts. It is incumbent upon the research community to ensure that these assessments are reliable so they can be justifiably employed by decision makers at all levels. They need to provide a picture of learner performance that is as accurate as possible, in a way that resists attempts to distort results by "teaching to the test." Once this has been accomplished, policy makers need to embrace these new assessment methods, and use them to take steps to improve the educational process. Only then will the revolutionary potentials of the Cyberinfrastructure for Education and Learning for the Future be achieved.

7. Conclusions

This report has presented a vision of a Cyberinfrastructure for Education and Learning for the Future (CELF). Cyberinfrastructure is seen as allowing unprecedented access to educational resources—including mentors, experts, online educational activities, games and virtual environments—and as providing learners with opportunities to interact with tools of professional science (scientific models, simulations, data sets, sensors and instruments). This is coupled with timely, accurate assessment and recording of student learning, which will make it possible to collect and analyze data from millions of educational activities nationwide. This will inevitably increase resources, possibilities and challenges for teachers and other educators.

CELF is not limited to the classroom, but will transcend the boundaries of formal education, informal learning, and lifelong learning as it addresses all stages from “pre-K to gray.” In so doing, it enables more inclusive and accessible education. It will provide the necessary platform for large-scale research on education and the sciences of learning. This, in turn, will enable new advances in both the sciences of learning and in the technologies used in learning and assessment that have the prospect of scaling and impact if effective public-private partnerships can be established (Pea et al., 2003, see footnote 67).

We have acknowledged the tendency to claim technological innovations as providing a “magic bullet” to cure education ills; however, we argue that there are substantial long-term benefits from using Cyberinfrastructure for learning. These include help in recruiting and educating the next generation of scientists, teachers, and citizens who are literate in STEM disciplines, as well as continuing to support the professional practices of current scientists and educators.

We considered four illustrative CELF themes: 1) blending formal and informal learning, 2) lifelong learning chronicles, 3) teaching through the Cyberinfrastructure, and 4) communities of learners. Each presents considerable opportunities and benefits for learning and education, as well as potential risks that must be overcome. They require major technological innovation and present considerable research challenges to the education, learning sciences, and computing communities.

The vision presented in this report cannot be realized without transforming facets of the wider context in which CELF is situated. Consequently, we have begun to consider the significant societal and policy changes that would be needed in order to realize this vision.

Appendix A. List of Workshop Participants

Workshop 1
Modeling, Simulation and Gaming Technologies Applied to Education
September 27-29, 2004

Sasha Barab	Indiana University
Janis Cannon-Bowers	University of Central Florida
Idit Caperton	MaMaMedia Inc
Justine Cassell	Northwestern University
Steve Cutchin	San Diego Supercomputer Center
Chris Dede	Harvard University
Erik Duval	Katholieke Universiteit Leuven
Mike Eisenberg	University of Colorado
Carrie Heeter	Michigan State University
Henry Jenkins	Massachusetts Institute of Technology
W. Lewis Johnson	University of Southern California
Yasmin Kafai	University of California-Los Angeles
Roy Pea	Stanford University
Marc Prensky	Games 2 Train Corp.
William Sandoval	University of California-Los Angeles
Brian M. Slator	North Dakota State University

Workshop 2
Cognitive Implications of Virtual or Web-Enabled Environments
November 30 – December 1, 2004

Shaaron Ainsworth	University of Nottingham
James Anderson	Brown University
Amy Baylor	Florida State University
Carole R. Beal	University of Southern California
Marie Bienkowski	SRI
Clark Chinn	Rutgers University
Susan Goldman	University of Illinois-Chicago
James Hollan	University of California-San Diego
Don Janelle	University of California-Santa Barbara
Kenneth Koedinger	Carnegie Mellon University
Jay Lemke	University of Michigan
Nancy Nersessian	Georgia Institute of Technology
Yvonne Rogers	Indiana University
Wes Shumar	Drexel University
Ronald Stevens	University of California-Los Angeles
Stephanie Teasley	University of Michigan
Umesh Thakkar	National Center for Supercomputing Applications
David Uttal	Northwestern University
Jennifer Wiley	University of Illinois-Chicago

Workshop 3
How Emerging Technology and Cyberinfrastructure Might Revolutionize the Role of Assessment in Learning
February 16-17, 2005

Sivakuma Alagumalai	University of Adelaide
Christine L. Borgman	University of California-Los Angeles
Neil Heffernan	Worcester Polytechnic Institute
Margaret Honey	Education Development Center
Sherry Hsi	Exploratorium
Steve Klein	RAND Corp.
Kenneth Koedinger	Carnegie Mellon University
Claudia Leacock	Pearson Knowledge Technologies
Bill Penuel	SRI
Mimi Recker	Utah State University
K. Ann Renninger	Swarthmore College
Gloria Rogers	ABET, Inc.
Valerie Shute	Educational Testing Service
Jennifer Turns	University of Washington

Workshop 4
The Interplay Between Communities of Learning or Practice and Cyberinfrastructure
March 24-25, 2005

Rick Adrion	University of Massachusetts-Amherst
Amy Bruckman	Georgia Institute of Technology
Kevin Clark	George Mason University
Anthony DePass	Long Island University
Joni Falk	TERC, Inc., and MSPnet
J.C. Herz	Author
Eric Hsu	San Francisco State University
Ted Kahn	DesignWorlds for Learning, Inc.
Marcia C. Linn	University of California-Berkeley
Mary Marlino	Digital Library for Earth Systems Simulation
Brandon Muramatsu	Utah State University
Jim Myers	Pacific Northwest Laboratory
Yael Ravin	IBM
Mary Beth Rosson	Pennsylvania State University
Mark Schlager	SRI and tappedin.org
Deborah Tatar	Virginia Tech University
Alf Weaver	University of Virginia
Stephen Weimar	The Math Forum
Gerry Wheeler	National Science Teachers Association

Appendix B. Workshop Questions

Participants were asked to respond to a series of questions prior to attending each workshop. Their answers served to frame the discussion and to provide the other participants with insight into the various perspectives included.

Workshop 1
Modeling, Simulation and Gaming Technologies Applied to Education

1. What is the potential of these technologies for learning of science, technology, engineering and mathematics (STEM)? Could they enable new kinds of learning?
2. What are examples of products or prototypes that you think represent a significant future trend? (Provide enough information for us to follow up on details.)
   a. Are these products or prototypes (as a category) designed to enable learning of particular STEM content?
   b. Are these products or prototypes designed for particular types of learners (age group, informal/personal leisure/formal, gender, or other characteristics such as particular learning preferences)?
   c. What technology infrastructure is needed or assumed for large-scale use, in either formal (e.g., school) or informal (e.g., museum or home) learning environments?
3. Who are leading players in the field as a researcher or a developer?
4. Who has a stake in the future of the application to learning and why?
5. Name some areas of research that would advance the application of the technology to learning in five to ten years.
6. What should NSF's role be in promoting the application of this technology to learning in the next five to ten years?
7. Are there 3 to 5 key citations you would recommend?

Workshop 2
Cognitive Implications of Virtual or Web-enabled Environments

1. What are the most critical research and development questions in both cognitive science and technology that will drive our understanding of how virtual learning environments can be used to radically transform Science, Technology, Engineering and Mathematics (STEM) learning?
2. What are the potential benefits and pitfalls with virtual learning environments, from both the cognitive and technological perspective?
3. What are the most exciting possibilities for virtual learning environments to enhance STEM learning over the next five years?
4. Considering advances in both technology and cognitive theory, how might virtual learning environments transform both the content and the delivery of STEM education in both formal (universities and schools) and informal (home, museums, on-line learning communities) settings?
5. What other experts, references, organizations, should NSF consult as we develop a five year research plan?

Workshop 3

How Emerging Technology and Cyberinfrastructure Might Revolutionize the Role of Assessment in Learning

1. How might cyberlearning technologies enable us to pose assessment questions that were, in the past, practically impossible to address? What questions are most important, and who (e.g., students, teachers, administrators, employers or policymakers) will benefit from answers to them?
2. What opportunities will new technologies afford for developing innovative assessment methods, especially ones that collect and analyze fine-grained data on Science, Technology, Engineering and Mathematics (STEM) learning and performance? How will these methods integrate education research and practice?
3. What are the prospects for continuous evaluation and assessment in STEM learning? How will this affect our ability to dynamically adapt educational designs and tailor learning experiences to meet the affective, cognitive and social needs of diverse groups of students?
4. What new roles will teachers play in classrooms and learning environments that incorporate technology-enabled assessments, and what tools will they need to play them effectively?
5. What are the risks as well as benefits of new technology-enabled assessments? For example, what are the potential dangers of establishing and sharing persistent portfolios of students' learning and performance? What are the current constraints (policy, cultural, technological and legal) on introducing invasive automatic assessment into learning environments? What new policies and tools can mitigate the risks?
6. What other experts, references, and organizations should NSF consult as we develop a research plan for the next 5 years—and beyond?

Workshop 4

The Interplay Between Communities of Learning or Practice and Cyberinfrastructure

1. How are current communities of learning or communities of practice that are facilitated by cyberinfrastructure different from earlier examples?
2. What new aspects of communities of learning owe their existence particularly to cyberinfrastructure? What aspects of earlier communities of learning are particularly enhanced by cyberinfrastructure? In both cases, why are these of interest and of value?
3. Why is it important to understand the intracommunity interaction dynamics in communities of learning and how does cyberinfrastructure permit the capture and analysis of these dynamics? What questions about these dynamics are important to ask, but cannot currently be answered? What advances in cyberinfrastructure would enable these questions to be answered?
4. What are the policy implications and issues that accompany investigations of behavior within communities of learning, for example, privacy and confidentiality?
5. What does it mean to belong to a community of learning or practice? If cyberinfrastructure enables a broader "membership" that cuts across "traditional boundaries" what, if any, are the advantages or disadvantages? Do "members" naturally evolve certain roles? What is the role of face-to-face interaction?
6. What is responsible for the persistence or sustainability of communities of learning/ practice and what if any is the role of cyberinfrastructure? Can aspects of cyberinfrastructure actually inhibit persistence? Is there such a thing as an ideal size for a community of learning? What is the role of face-to-face interaction?
7. Assuming that not all communities of learning/practice are alike, is there a taxonomy for communities of learning/practice?
8. What other questions are important to ask about communities of learning and cyberinfrastructure?
9. What other experts, references, and organizations should NSF consult as it develops a research and development plan for the next 5 years—and beyond?

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