Cyberinfrastructure and the Evolution of Higher Education

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Overview

Over the next decade, in what ways will advances in computers and telecommunications impact various dimensions of higher education and shape its evolution? This is a pivotal time for sketching the impact of information and communications technologies on colleges and universities because emerging tools, applications, media, and infrastructures are reshaping three aspects of instruction and scholarship simultaneously:

- The knowledge and skills that society wants from the graduates of higher education are shifting, due to the evolution of a global, knowledge-based economy in a “flat” world.¹
- Methods of research, teaching, and learning are expanding as new interactive media support innovative forms of pedagogy.²
- The characteristics of students are changing as their use of technology outside academic settings shapes their learning styles, strengths, and preferences.³

For all these reasons, advances in computers and telecommunications have a powerful effect on higher education.

This ECAR research bulletin discusses the role cyberinfrastructure will play as higher education evolves. Changes in the job markets, in higher education research and teaching, and in emerging academic disciplines are having a direct impact on, and will be directly impacted by, information technologies. As national councils acknowledge, higher education has an enormous stake in these crucial and sweeping changes.

Highlights of Cyberinfrastructure and the Evolution of Higher Education

In the report “Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,”⁴ sweeping changes to make college and university teaching more effective are seen as crucial to our nation’s ability to compete in the emerging global, knowledge-based economy. Some of the report’s recommendations are targeted at improving instruction at every level of American education and ensuring that all students are taught in ways that encourage and enable them to realize their intellectual talents. Other recommendations involve increased investment in higher education, such as 5,000 new graduate fellowships per year in “areas of national need,” as well as a $500 million fund for advanced research instrumentation and facilities.

This call to action echoes a variety of national reports⁵ about global competitiveness, U.S. economic development, and education, all of which have expressed similar concerns. These calls to action highlight comparable, interrelated themes.⁶

The next decade will determine the future of the U.S. economy for generations to come. Never before has the U.S. faced global competition of the magnitude seen today. Systems of economic development based on geography, trade rules, and tariffs; slow
dissemination of scientific and technological discoveries; and long cycles of product life have given way to global trade, rapid product innovation, the lowering of trade barriers, rapid dissemination of scientific and technological discovery, and rapid global deployment and movement of capital and the means of production. Competitive advantage for a region, state, or nation is now built on the skills of its general workforce as opposed to its geography, trade laws, research labs, and patents. Markets in the New Economy are rewarding those who have high educational achievement and technical skill. The worker of the 21st century must have science and mathematics skills, creativity, information and communication technologies skills, and the ability to solve complex problems. Novel ideas, discoveries, and technologies have produced whole new industries and products; innovation is now the primary basis for income and wealth generation.

Each of these reports stresses that U.S. schooling at every level, including higher education, has not yet transformed to meet these interrelated challenges.

**Information Technologies and the New Job Market**

Such an educational transformation necessitates the sophisticated usage of information and communication technologies, since these are largely responsible for creating a “flat” world and knowledge-based economies generating the socioeconomic shifts detailed above. Levy and Murnane document how:

- Declining portions of the labor force are engaged in jobs that consist primarily of routine cognitive work and routine manual labor—the types of tasks that are easiest to program computers to do. Growing proportions of the nation’s labor force are engaged in jobs that emphasize expert thinking or complex communication—tasks that computers cannot do.

These economists go on to explain that “expert thinking” involves “effective pattern matching based on detailed knowledge, and metacognition, the set of skills used by the stumped expert to decide when to give up on one strategy, and what to try next.” “Complex communication” requires “the exchange of vast amounts of verbal and nonverbal information. The information flow is constantly adjusted as the communication evolves unpredictably.” Expert thinking and complex communications at their highest level are the core of higher education.

Over the next couple of decades, how might these factors combine to transform the nature of research and education in colleges and universities? One strategic initiative shaping this issue has developed through the National Science Foundation’s emergent conception of “cyberinfrastructure” as a means of actualizing the promise of sophisticated information and communication technologies in instruction and scholarship.

**Cyberinfrastructure for Research and Teaching**

In recent years, the NSF has championed a vision of the future of research that centers on cyberinfrastructure: the integration of computing, data and networks, digitally enabled
sensors, observatories and experimental facilities, and an interoperable suite of software and middleware services and tools.\textsuperscript{11} Gains in computational speed, high-bandwidth networking, software development, databases, visualization tools, and collaboration platforms are reshaping the practices of scholarship and beginning to transform teaching. Sophisticated simulation software and distributed, wireless observation networks are enabling the exploration of phenomena that cannot be studied through conventional experimental methods. Computational models, such as those based on chaos theory, are dramatically extending the limited range of models available through mathematics alone. “Fewer and fewer researchers working at the frontiers of knowledge can carry out their work without cyberinfrastructure of one form or another.”\textsuperscript{12}

Cyberinfrastructure developed for research purposes also creates intriguing opportunities to transform higher education. “New methods to observe and to acquire data, to manipulate it, and to represent it challenge the traditional discipline-based graduate curricula.”\textsuperscript{13} Scientific and educational resources can now pervade a wide variety of settings, rather than being accessible only in limited, specialized locations. Real-time data collection can enable assessing students’ educational gains on a formative basis, providing insights into the microgenetics of learning the complex knowledge and skills characteristic of higher education. Students can customize personal learning environments to a degree never before possible. Extensive online learning can complement conventional face-to-face education, and ubiquitous, pervasive computing can infuse smart sensors and computational access throughout the physical and social environment.

Accomplishing these shifts requires more than the creation and maintenance of the cyberinfrastructure itself:

To employ the tools and capabilities of cyberinfrastructure-enabled learning environments effectively, teachers and faculty must also have continued professional development opportunities. For example, teachers and faculty must learn to use new assessment techniques and practices enabled by cyberinfrastructure, including the tailoring of feedback to the individual, and the creation of personalized portfolios of student learning that capture a record of conceptual learning gains over time. These conditions permit new learning organizations to form, raising in turn new research questions about the creation, operation, and persistence of communities of practice and learning. In such cyberlearning networks people will connect to learn with each other, even as they learn to connect with each other, to exploit increasingly shared knowledge and engage in participatory inquiry.\textsuperscript{14}

**Emerging Disciplines**

New disciplines may result from these emerging methods of education, fields as important as the relatively new areas of computer science, mathematical biology, genomics, environmental science, and astrophysics are today.

During 2004 and 2005, with NSF funding, the Computing Research Association (CRA) convened four workshops, attended by experts in education, with four distinct foci:\textsuperscript{15}
- Modeling, Simulation, and Gaming Technologies Applied to Education
- Cognitive Implications of Virtual or Web-enabled Environments
- How Emerging Technology and Cyberinfrastructure Might Revolutionize the Role of Assessment in Learning
- The Interplay Between Communities of Learning or Practice and Cyberinfrastructure

Collectively, these groups envisioned 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. 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.\(^{16}\)

Members of the expert workshops posited that the influence of cyberinfrastructure on education extends well beyond mere second-order effects of its impact on research. They noted that earlier work foundational to cyberinfrastructure had shaped the evolution of learning and teaching. As one example, the NSF-funded National Science Digital Library (NSDL), which was created to enable widespread access to resources and tools that support innovations in teaching and learning, now contains over 800,000 items from 500 partner libraries and is an important aid in educational improvement at all levels.\(^{17}\)

The CRA report details projected shifts in education that cyberinfrastructure will facilitate as it develops. Some of these resonate with the visions of improving higher education described earlier. As an illustration of CRA’s forecasts about the evolution of learning and teaching, the report notes:

As STEM [science, technology, engineering, and mathematics] 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; 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.\(^{18}\)
However, the report cautions that networked systems can create unexpected side-effects, citing usage of data and privacy and accessibility, as well as the potential intertwining of formal schooling and assessment with ubiquitous informal learning.

The NSF Cyberinfrastructure Council provides a scenario of how advanced visualization and simulation capabilities could advance education:

Imagine an interdisciplinary course in the design and construction of large public works projects, attracting student-faculty teams from different engineering disciplines, urban planning, environmental science, and economics; and from around the globe. To develop their understanding, the students combine relatively small self-contained digital simulations that capture both simple behavior and geometry to model more complex scientific and engineering phenomena. Modules share inputs and outputs and otherwise interoperate. These “building blocks” maintain sensitivity across multiple scales of phenomena. For example, component models of transportation subsystems from one site combine with structural and geotechnical models from other collections to simulate dynamic loading within a complex bridge and tunnel environment. Computational models from faculty research efforts are used to generate numerical data sets for comparison with data from physical observations of real transportation systems obtained from various (international) locations via access to remote instrumentation. Furthermore, learners explore influences on air quality and tap into the expertise of practicing environmental scientists through either real-time or asynchronous communication. This networked learning environment increases the impact and accessibility of all resources by allowing students to search for and discover content, to assemble curricular and learning modules from component pieces in a flexible manner, and to communicate and collaborate with others, leading to a deep change in the relationship between students and knowledge. Indeed, students experience the profound changes in the practice of science and engineering and the nature of inquiry that cyberinfrastructure provokes.¹⁹

Comparable vignettes can illustrate educational opportunities in constellations of fields across the sciences and social sciences.

The CRA report on educational visions for cyberinfrastructure also presents a vignette of a “serious game”:

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.

What It Means to Higher Education

One may ask why colleges and universities should track the evolution of pre-college schooling. Improvements in K–12 teaching will influence the knowledge, skills, attitudes, and learning styles of students entering higher education. If in the future entering students have deeper understandings and more sophisticated skills than current initiates, this shift offers the opportunity to reconceptualize higher education toward inculcating more advanced knowledge than currently possible.

In fact, pre-college, undergraduate, and graduate education may link more closely together should the digital Lifelong Learning Chronicles (LLCs) envisioned in the CRA depiction of educational cyberinfrastructure come to pass:

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. 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.\textsuperscript{21}

To the extent that research communities also engage in forms of individual and collective learning, advances in instructional design based on LLCs as a record of microgenetic learning may also empower faster and deeper evolution of insights by scholars, particularly in graduate university settings.

However, realizing all these benefits of educational cyberinfrastructure depends on faculty transforming their instructional practice to take advantage of these new capabilities. For most instructors, such a shift will require extensive professional development, even though they may already have made comparable changes in how they conduct their research. The CRA report notes the potential of cyberinfrastructure for meeting this professional development challenge:

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. 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.\textsuperscript{22}

Past experience has shown that colleges and universities would need to provide substantial incentives to persuade many faculty to undertake such professional development. Without policies that promote change, psychological and cultural barriers are likely to impede evolution long after technical and economic challenges are overcome.

Thoughtful and caring participation by faculty is vital for making cyberinfrastructural capabilities truly valuable in complementing face-to-face interactions with students and colleagues. How a medium shapes its users, as well as its message, is a central issue in understanding the transformation of conventional classroom education into learning that prepares students for the 21st century. The telephone creates conversationalists; the book develops imaginers, who can conjure a rich mental image from sparse symbols on a printed page. Much of television programming induces passive observers; other shows, such as Sesame Street and public affairs programs, can spark users' enthusiasm and enrich their perspectives. We are all struggling to understand what types of people might be fostered by online sociosemantic networks and virtual organizations. Many faculty view the shifts described above with deep suspicion. I have
colleagues who hope to retire before they are forced to acknowledge that, as with other professions, the old ways of instruction and scholarship are no longer best. Yet many more of us welcome the opportunity for renewal that advanced information and communications technologies offer and hope to serve a vital role in their development, tempering the new ideas they offer with wisdom and experience based on the strengths and limits of older educational media.

Key Questions to Ask

- How is our institution using cyberinfrastructure to actualize the use of sophisticated information and communication technologies in instruction and scholarship?
- In what ways does our institution measure the degree to which we are keeping pace with gains in computational speed, high-bandwidth networking, software development, visualization tools, and collaboration platforms?
- What professional development programs are in place for faculty to learn to use new pedagogical and assessment techniques enabled by cyberinfrastructure, including personalized portfolios of student learning?

Where to Learn More


Endnotes


9. Ibid., 75.

10. Ibid., 94.

12. Ibid., 5.

13. Ibid., 38.


16. Ibid., 1.

17. Ibid., 4.

18. Ibid., 5–6.


22. Ibid., 26.

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