Higher Learning in the Digital Age:

An Update on a National Academies Study

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Introduction

It was just about a decade ago, when one of my colleagues, Dan Atkins, dropped off a little piece of software he had picked up at the University of Illinois and asked me to give it a spin over the holiday season. It was MOSAIC…and my days as a "Gopher" and "FTP-er" had come to an end.

Fortunately, so too had Michigan's collaboration with IBM and MCI in building and managing the backbone network for NSFnet, later NREN, and eventually what today we call the Internet, since the introduction of the browser triggered an avalanche of demand and growth that would have overwhelmed an academic institution.

Yet a decade ago, many people had yet to accept that the inexorable progress of information technology (IT) would result in fundamental change in universities–particularly in that species known as the research university.

To be sure, our research universities not only created much of this technology; our faculty and students were leaders in its application. But we had yet to accept that the rapid evolution of digital information and communications technologies such as the World Wide Web could reshape our universities much as would reshape other sectors of our society.

The National Academies Study

It was this concern that stimulated the National Academies of the United States (i.e., the National Academy of Science, the National Academy of Engineering, the Institute of Medicine, and their umbrella research organization, the National Research Council) to launch a major project to understand better just how this technology was likely to affect the research university, a project that I have been chairing for the past three years.

Here it should be noted that the National Academies have a mandate to track the health of the nation's scientific and technological capability, and the nation's research universities represent a very significant component of that intellectual infrastructure.

The premise of the National Academies studies was a simple one: The rapid evolution of digital technology will present many challenges and opportunities to higher education in general and the research university in particular. Yet there was a sense that many of the most significant issues are neither well recognized nor understood either by leaders of our universities or those who support and depend upon their activities.

The first phase of the project was aimed at addressing three sets of issues:

1. To identify those technologies likely to evolve in the near term (a decade or less) that might have major impact on the research university.

2. To examine the possible implications of these technology scenarios for the research university: its activities (teaching, research, service, outreach); its organization, structure, management, and financing; and the impact on the broader higher education enterprise and the environment in which it functions.

3. To determine what role, if any, there was for our federal government and other stakeholders in the development of policies, programs, and investments to protect the valuable role and contributions of the research university during this period of change.

The steering group for the effort was comprised of leaders from higher education, the chief technology officers of major IT companies, and leaders in national science policy. Over two years the steering group met on numerous occasions to consider these issues, including site visits to major technology

laboratories such as Bell Labs and IBM Research Labs and drawing upon the expertise of the National Academy complex. At the end of this period, we assembled over 100 leaders from higher education, the IT industry, and the federal government, and several private foundations for a two-day workshop at the National Academy of Sciences to focus our discussion. Beyond the insight brought by these participants, perhaps even more striking was their agreement on a number of key issues:

The first finding of the Academies' steering committee was that the extraordinary pace of the IT evolution is likely not only to continue but could well accelerate.

In thinking about changes to the university, one must think about the technology that will be available in 10 or 20 years, technology that will be thousands of times more powerful as well as thousands of times cheaper. Put another way, over the next decade, we will evolve from "giga" technology (in terms of computer operations per second, storage, or data transmission rates) to "tera" and then to "peta" technology (one million-billion or 10^{15}). We will denominate the number of computer servers in the billions, digital sensors in the tens of billions, and software agents in the trillions. The number of people linked together by digital technology will grow from millions to billions. We will evolve from "e-commerce" and "e-government" and "e-learning" to "e-everything", since digital devices will increasingly become our primary interfaces not only with our environment but with other people, groups, and social institutions.

The second finding of the committee, in the words of North Carolina State University chancellor Mary Anne Fox, was that the impact of IT on the university is likely to be "profound, rapid, and discontinuous," affecting all of its activities (teaching, research, service), its organization (academic structure, faculty culture, financing, and management), and the broader higher education enterprise as it evolves toward a global knowledge and learning industry.

If change is gradual, there will be time to adapt gracefully, but that is not the history of disruptive technologies. As Clayton Christensen explains in *The Innovators Dilemma*,[1] new technologies are at first inadequate to displace existing technology in existing applications, but they later explosively displace the application as they enable a new way of satisfying the underlying need.

Although it may be difficult to imagine today's digital technology replacing human teachers, as the power of this technology continues to evolve 100- to 1000-fold each decade, the capacity to reproduce with high fidelity all aspects of human interactions at a distance could well eliminate the classroom and perhaps even the campus as the location of learning. Access to the accumulated knowledge of our civilization through digital libraries and networks, not to mention massive repositories of scientific data from remote instruments such as astronomical observatories or high-energy physics accelerators, is changing the nature of scholarship and collaboration in very fundamental ways. Each new generation of supercomputers extends our capacity to simulate physical reality to a higher level of accuracy, from global climate change to the biological function at the molecular level.

The third finding of the committee suggests that although information technology will present many complex challenges and opportunities to universities, procrastination and inaction are the most dangerous courses to follow during a time of rapid technological change.

Because of the profound yet unpredictable impact of this technology, we urged universities to adopt strategies that included:

1) the opportunity for experimentation,
2) the formation of alliances both with other academic institutions as well as with for-profit and government organizations, and
3) the development of sufficient in-house expertise among the faculty and staff to track technological trends and assess various courses of action.

The first phase of this study, its conclusions, and its recommendations were published in a report, *Preparing for the Revolution*, available both online and through hard copy from the National Academy Press.[2]

The IT-Forum

More recently, the National Academies have extended this effort to involve directly a large number of research universities by

1) creating a National Academy Forum on Information Technology and Research Universities to track the technology and identify the key issues,
2) conducting a series of workshops for university presidents and chief academic officers in an effort to help them understand better the transformational nature of these technologies and the importance of developing strategic visions for the future of their institutions, and
3) raising the awareness of research sponsors such as nonprofit foundations and government agencies as to the potential of these technologies for engaging research universities to better address national and global priorities.

These events revealed not only a broad interest in and awareness of the importance of these issues, but a willingness to explore new paradigms such as national consortia, open-source projects, and knowledge commons. It was our sense that the leadership of U.S. research universities is prepared to undertake major efforts and consider very substantial changes (in organization, function, and culture) to respond to the opportunities and challenges posed by information technology.

The AAU Presidents' Workshop (April 15, 2003)

We first targeted the presidents of the nation's leading research universities, namely those members of the Association of American Universities, by asking them to stay for a daylong workshop following their annual meeting last spring.

Heading the old adage that to get a mule to move, you first need to whack it over the head with a 2x4, we asked Lou Gerstner, former CEO of IBM, to kick off the meeting the evening before with a dinner address, describing how he had transformed IBM. Gerstner made two key points that quickly gained the presidents' attention. He noted that when he arrived at IBM during the early 1990s, IBM's stock value was plummeting and there was serious consideration given to breaking the company up because d espite the fact that IBM was developing much of this technology, the company really didn't understand the implications of its disruptive character for their own corporation. Furthermore, technology strategies require the attention of the very highest level of an organization's leadership. To simply delegate this assignment to others such as CIOs or CFOs puts the organization at great risk.

With full awareness that university presidents listen most carefully to their own voices, we structured workshop the next day into panels of presidents:

First, we asked several presidents (including Chuck Vest-MIT, Nancy Cantor-U. Ilinois, James Moeser-U. North Carolina, and Bob Berdahl-UC-Berkeley) to discuss what was currently in their in-out box, the here-and-now issues. As you can imagine, these included concerns such as how they could meet the seemingly insatiable demand for computing resources (particularly bandwidth); how they could pay for this technology; and how they could handle privacy and security issues. You will also probably not be surprised that most of the presidents boasted that they had these issues well in hand (a perception quite different than we were to find with their provosts several months later).

We then tried to move the presidents group somewhat farther into the future, by asking them to speculate about technology challenges for the decade ahead. Here, we stimulated the discussion by having members of the IT Forum toss occasional hand grenades into the conversation.

For example, Stu Feldman of IBM asked how the presidents would respond to the strong possibility that he would be able to hand them a device the size of a

football (choosing an object particularly familiar to university presidents) that would contain the entire Library of Congress.

Dan Atkins (Michigan), coming off his recent experience as chair of the NSF Blue Ribbon Panel on Cyberinfrastructure, asked how the presidents believe faculty loyalty and mobility would be affected by the rapid emergence of knowledge nets, cyberspace-based environments for scientific collaboration clearly independent of space and time.

Bob Dynes (UC San Diego) observed that technology is moving so fast that there are vast differences between the seniors and the freshmen at his institution. The freshmen are completely wireless, and communicating in very unexpected ways. If we enable students, they will drive us. He also noted that campus boundaries are less and less meaningful, which poses additional challenges.

Stu Feldman (IBM) raised two more important questions: (1) Is it possible to manage universities as unified enterprises, or will they always function as decentralized entities? and (2) Will the university build its value proposition around the student (e.g. the University of Phoenix) or the professor? He noted the degree to which E-infrastructure could disintegrate, disaggregate, reintegrate and reaggregate functions and roles of a university. The real disruptive force is the marketplace, brought onto campuses by new technologies in a highly competitive and disruptive fashion He questioned whether the current package of activities that have emerged as the U.S. research university will survive intact.

Bill Wulf noted that past predictions of future social impacts from technological advance have been notably bad. They typically assume some version of the status quo, only faster, cheaper, bigger, etc. that is quickly blown apart by unanticipated.

After about an hour of this wide-ranging discussion, Bob Berdahl, chancellor of UC-Berkeley, stood up and said: “OK. Now you have convinced me. This

technology is creating a future that is so uncertain that I don't have a clue how presidents can provide effective leadership. We need your help!"

Hence, we had managed to bring the group far along the "seven stages of death", from denial to acceptance to bargaining to seeking help…

The AAU Provosts' Workshop (September 9, 2003)

We had an opportunity to conduct a very similar workshop for the AAU provosts, following their September meeting in Newport Beach, California. This was organized very similarly to the AAU Presidents' workshop, by first asking a panel of provosts to lay out the issues as they saw them at the moment, then to move the discussion to a longer-term perspective, and finally to conclude with a discussions of next steps.

It is probably not surprising that many of the near term issues raised by the provosts were very similar to those raised by the presidents:

Network and bandwith management
How do we pay for this technology
How do we protect security and privacy?
Data management and preservation issues

We next tried to bump the discussion up a notch to look at longer-term issues such as:

The digital generation (students and faculty)
The emerging needs for cyberinfrastructure
Competition vs. cooperation
The instability of the current research university paradigm
The survival of the research university (an issue that would have been hard to put on the table with the university presidents)

Perhaps not surprising was a far greater degree of sophistication among the provosts in understanding and addressing these issues than shown by the

presidents. But there was an even more significant difference: unlike the presidents, the provosts already recognized that these were very difficult issues, and they certainly didn't have the answers. This was also an interesting contrast with a quite similar workshop on technology held five years earlier when the provosts neither understood nor accepted the strategic nature of technology issues. Clearly these academic leaders have moved far beyond denial about the transformative nature of technology issues and are searching for effective strategies.

Some of the highlights of the discussion include:

There was a growing concern about the degree to which universities were being victimized by the effective monopolies created by providers such as PeopleSoft, Blackboard, and, of course, Microsoft. As one provost put it, universities act like deer paralyzed in the oncoming headlights, continuing to re-invent the wheel and getting devoured by the marketplace. The provosts were essentially unanimous in their belief that it was time for the research universities to set aside their competitive instincts and to build consortia to develop together the technologies to support their instructional, research, and administrative needs through an open-source paradigm that would break the stranglehold of the current marketplace. Similar cooperation was needed in areas of cyberinfrastructure such as Internet2, the Open Knowledge Initiative, SAKAI, and the Open CourseWare effort.

Lloyd Armstrong (USC) noted that universities are a fractal representation of broader society, and the imperatives of security and privacy in IT (and particularly the Internet) represented broader strategic issues for our world.

Many provosts suspected that while the faculty believed they knew how their students learned, in reality they didn't have a clue, particularly in technology-rich environments. Universities need far more sophisticated help (perhaps through NSF-sponsored programs) to understand the learning and cognitive processes, although the provosts also recognized the disruptive nature of these

studies which might eliminate over time the rationale for the lecture-classroom paradigm.

The workshop concluded with a very broad ranging discussion concerning very fundamental issues such as the mission, roles, values, and traditions of the university. Susanne Lohmann (UCLA) reminded the group that during the 1865-1900 period, over a single generation, American higher education changed essentially every one of its characteristics in a radical fashion, evolving from the colonial colleges to the Humboltian model of a research university, empowering the faculty, growing from institutions with hundreds to thousands of students, and through the land-grant movement, creating the new paradigm of the engaged public university. Everything that could change, in fact, did change. Many in the AAU Provosts' workshop believed that we are well along in a similar period of dramatic change in higher education.

IT-Forum Meeting at Carnegie Mellon University on "Cogniition, Communication, and Communities" (September 5, 2003)

To learn more about how learning occurs in technology-intensive environments, we held the September meeting of the IT Forum at Carnegie Mellon, famous both as one of the nation's most wired–and now wireless–campuses, and also for its great strength in the cognitive sciences.

As the faculty put it, their students these days are "electrified". They are a transformative force, frequently forcing the CMU faculty to react to their learning activities. An example is the way students use this technology for communication. From instant messaging to e-mail to WiKi's to Blogs, students are in continual communication with one another, forming groups or entire communities that are always interacting, even in classes (as any faculty member who has been "Googled" can attest).

A second example: a young professor of physics told us he had been forced to give up trying to "teach" difficult concepts in his classes. Instead he introduces a

topic by pointing to several resources until a few students in the class figure it out a way to teach themselves the concept. Then they teach their fellow students, and through peer-to-peer learning, the concepts propagate rapid through the class.

As Kevin Kelly (Wired) put it, the CMU students are using instant messaging and Google to create their own learning environments. THEY will determine not only which learning technologies but as well, which learning methods work best. The faculty is reduced to catching up to formalize what the students have developed.

In fact, many CMU faculty have now concluded that perhaps the best approach is to turn the kids loose, to let information learning lead and shape formal learning in a way that responds to the great diversity in how students learn. Peer-to-peer learning is rapidly replacing faculty teaching as the dominant educational process on this technology-rich campus. There is not yet a consensus among the faculty as to where they are headed, but there is strong agreement that IT is changing the learning process in very fundamental ways.

Further IT-Forum Discussions on Learning

This technology is forcing us to rethink the nature of literacy.

> From literacy in the oral tradition
> To the written word
> To the images of film and then television
> To the computer and multimedia

Of course there are many other forms of literacy: art, poetry, mathematics, science itself, etc. But more significantly, the real transformation is from literacy as "read only, listening, and viewing" to composition in first rhetoric, then writing, and now in multimedia.

From another perspective, our society increasingly values not just analysis but synthesis, enabled by the extraordinary tools of the digital age. Increasingly, we realize that learning occurs not simply through study and contemplation but through the active discovery and application of knowledge. From John Dewey to Jean Piaget to Seymour Papert, we have ample evidence that most students learn best through inquiry-based or "constructionist" learning.

As the ancient Chinese proverb suggests "I hear and I forget; I see and I remember; I do and I understand."

To which I might add, "I teach and I master!!!"

But herein lies a great challenge. While universities are experienced in teaching the skills of analysis, we have far less understanding of the intellectual activities associated with creativity. In fact, the current disciplinary culture of our campuses sometimes discriminates against those who are truly creative, those who do not fit well into our stereotypes of students and faculty.

The university may need to reorganize itself quite differently, stressing forms of pedagogy and extracurricular experiences to nurture and teach the art and skill of creation. This would probably imply a shift away from highly specialized disciplines and degree programs to programs placing more emphasis on integrating knowledge.

Perhaps it is time to integrate the educational mission of the university with the research and service activities of the faculty by ripping instruction out of the classroom–or at least the lecture hall–and placing it instead in the discovery environment of the laboratory or studio or the experiential environment of professional practice.

The traditional classroom paradigm is being challenged today, not so much by professors, who have by and large optimized their teaching effort and their time commitments to a lecture format, but by our students. Members of today's digital

generation of students have spent their early lives immersed in robust, visual, electronic media--Sesame Street, MTV, home computers, video games, cyberspace networks, MUDs and MOOS, and virtual reality.

Unlike those of us who were raised in an era of passive, broadcast media such as radio and television, today's students expect--indeed, demand--interaction. They approach learning as a "plug-and-play" experience. They are unaccustomed and unwilling to learn sequentially--to read the manual. Instead they are inclined to plunge in and learn through participation and experimentation. Although this type of learning is far different from the sequential, pyramidal approach of the traditional college curriculum, it may be far more effective for this generation, particularly when provided through a media-rich environment.

John Seely Brown and his colleagues at Xerox PARC have studied the learning habits of the plug-and-play generation and identified several interesting characteristics of their learning process. First, today's students like to do several things at once–they "multitask", performing several tasks simultaneously at a computer such as website browsing and e-mail while listening to music or talking on a cellular phone. Although their attention span appears short, as they jump from one activity to another, they appear to learn just as effectively as earlier generations.

Furthermore, it is clear that they have mastered a broader range of literacy skills, augmenting traditional verbal communication skills with visual images and hypertext links. They are particularly adept at navigating through complex arrays of information, acquiring the knowledge resources they seek and building sophisticated networks of learning resources.

To be sure, for a time, such students may tolerate the linear, sequential lecture paradigm of the traditional college curriculum. They still read what we assign, write the required term papers, and pass our exams. But this is decidedly not the way they learn. They learn in a highly nonlinear fashion, by skipping from beginning to end and then back again, and by building peer groups of learners,

by developing sophisticated learning networks in cyberspace. In a very real sense, they build their own learning environments that enable interactive, collaborative learning, whether we recognize and accommodate this or not.

However, their tolerance for the traditional classroom and four-year curriculum model may not last long. Students will increasingly demand new learning paradigms more suited to their learning styles and more appropriate to prepare them for a lifetime of learning and change

One can imagine the impact of millions of students from the digital generation as they seek the interactive, collaborative, and convenient learning experiences they have already experienced from other digital media. We should not underestimate the impact of the plug-and-play generation on the university.

After all, their use of digital technologies such as Napster and other peer-to-peer applications quickly overloaded our IT infrastructures and threatened the recording industry. Their use of the Net and other digital resources is already far more sophisticated than most faculty and staff. They will drive rapid and profound change in higher education since they will demand that we adapt the university to their learning needs and characteristics through market forces.

From another perspective, what is really going on here is the use by students of rapidly emerging digital technology to form learning communities.

The learning process as rooted both in experience and social interaction. Learning requires the presence of communities.

This is the value of the university--to create learning communities and to introduce students into these communities

Once we have realized that the core competency of the university is not simply transferring knowledge, but developing it within intricate and robust networks and communities, we realize that this is were the real impact of information

technology occurs. In true learning communities the distinction between teachers and students blurs. Both groups become active learners, working together to benefit each other.

In these new learning paradigms, the word *student* becomes largely obsolete, because it describes the passive role of absorbing content selected and conveyed by teachers. Instead we should probably begin to refer to the clients of the twenty-first-century university as active *learners,* since they will increasingly demand responsibility for their own learning experiences and outcomes.

In a similar sense, the concept of a *teacher* as one who develops and presents knowledge to largely passive students may become obsolete. Today, faculty members who have become experts in certain subfields are expected to identify the key knowledge content for a course based on their area of interest, to organize and then present the material, generally in a lecture format, in this course.

More specifically, faculty members of the twenty-first-century university will find it necessary to set aside their roles as teachers and instead become designers of learning experiences, processes, and environments. In the process, tomorrow's faculty members may have to discard the present style of solitary learning experiences, in which students tend to learn primarily on their own through reading, writing, and problem solving. Instead, they may be asked to develop collective learning experiences in which students work together and learn together, with the faculty member becoming more of a consultant or a coach than a teacher.

To understand this better, the spring meeting of the IT-Forum was held at the Institute for Creative Technologies in Marina del Rey. Here, the University of Southern California is applying the entertainment and gaming technologies developed by Hollywood and others to create a “holodeck” to use train military officers in higher level decision making. They have learned something that

universities have yet to grasp: how technology can be used to create an emotional connection between knowledge and learning.

Cyberinfrastructure

Our most recent activities have been stimulated by an important study by the National Science Foundation Blue Ribbon Advisory Panel on Cyberinfrastructure, chaired by Dan Atkins. The Panel concluded that we are approaching an inflection point in the potential of rapidly evolving information and communications technology to transform how the scientific and engineering enterprise does knowledge work, the nature of the problems it undertakes, and the broadening of those able to participate in research and the related educational activities. To quote the concluding paragraph of its report:

> "A new age has dawned in scientific and engineering research, pushed by continuing progress in computing, information, and communication technology, and pulled by the expanding complexity, scope, and scale of today's challenges. The capacity of this technology has crossed thresholds that now make possible a comprehensive 'cyberinfrastructure' on which to build new types of scientific and engineering knowledge environments and organizations and to pursue research in new ways and with increased efficacy. Increasingly, new types of scientific organizations and support environments for science are essential, not optional, to the aspirations of research communities and to broadening participation in those communities. They can serve individuals, teams, and organizations in ways that revolutionize what they can do, how they do it, and who participates. This vision has profound broader implications for education, commerce, and social good."[3]

While promising significant new opportunities for scientific and engineering research and education, the digital revolution will also pose considerable challenges and drive profound transformations in existing organizations such as universities, national and corporate research laboratories, and funding agencies

such as NSF. Here it is important to recognize that the implementation of such new technologies involve social and organizational issues as much as they do technology itself. Achieving the benefits of IT investments will require the co-evolution of technology, human behavior, and organizations.

There is a clear need to involve and stimulate as well those organizations that span disciplinary lines and integrate scholarship and learning. Perhaps the most important such organization is the research university, which despite the potential of new organizational structures, will continue to be the primary institution for educating, developing, and sustaining the American scientific and engineering enterprise.

But universities will need help, to understand, explore, and develop the cyberinfrastructure necessary to support their educational and scholarly activities. Indeed, without assistance, federal efforts such as those at NSF are unlikely to achieve their potential, since the existing culture, structure, and function of the research university will likely resist and possibly reject new approaches that challenge the status quo.

There is a sense among many in the research university community that we will see a convergence and standardization of the cyberinfrastructure necessary for state-of-the-art research and learning over the next several years, built upon open source technologies, standards, and protocols, and that the research universities themselves will play a leadership role in creating these technologies, much as they have in the past.

Concluding Remarks

To summarize, our studies thus far have led us to the following conclusions:

First, we believe the extraordinary evolutionary pace of information technology is likely to continue for the next several decades and even could accelerate on a superexponential slope. The event horizons for disruptive change are moving

ever closer. The challenge is getting people to think about the implications of accelerating technology learning curves as well as technology cost-performance curves is very important. There are likely to be major technology surprises, comparable in significance to the appearance of the personal computer in the 1970s, the World Wide Web in the 1980sm and the Internet browser in 1990s, but at more frequent intervals. The future is becoming less certain.

The impact of information technology on the university will likely be profound, rapid, and discontinuous--just as it has been and will continue to be for the economy, our society, and our social institutions (e.g., corporations, governments, and learning institutions). It will affect our activities (teaching, research, outreach), our organization (academic structure, faculty culture, financing and management), and the broader higher education enterprise as it evolves into a global knowledge and learning industry.

Yet, for at least the near term, meaning a decade or less, the university will continue to exist in much its present form, although meeting the challenge of emerging competitors in the marketplace will demand significant changes in how we teach, how we conduct scholarship, and how our institutions are financed. Universities must anticipate these forces, develop appropriate strategies, and make adequate investments if they are to prosper during this period.

Over the longer term, the basic character and structure of the university may be challenged by the IT-driven forces of aggregation (e.g., new alliances, restructuring of the academic marketplace into a global learning and knowledge industry) and disaggregation (e.g., restructuring of the academic disciplines, detachment of faculty and students from particular universities, decoupling of research and education).

Although we feel confident that information technology will continue its rapid evolution for the foreseeable future, it is far more difficult to predict the impact of this technology on human behavior and upon social institutions such as the

university. It is important that higher education develop mechanisms to sense the changes that are being driven by information technology and to understand where these forces may drive the university.

In summary, for the near term (meaning a decade or less), we anticipate that information technology will drive comprehensible if rapid, profound, and discontinuous change in the university. For the longer term (two decades and beyond), all bets are off. As we have noted implications of a million-fold increase in the power of information technology are difficult to even imagine, much less predict for our world and even more so for our institutions.

Although information technology will present many complex challenges and opportunities to university leaders, we suggest that procrastination and inaction are the most dangerous courses of all during a time of rapid technological change. After all, attempting to cling to the status quo is a decision in itself, perhaps of momentous consequence.

To be sure, there are certain ancient values and traditions of the university that should be maintained and protected, such as academic freedom, a rational spirit of inquiry, and liberal learning. But, just as it has in earlier times, the university will have to transform itself once again to serve a radically changing world if it is to sustain these important values and roles.

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[1] Clayton M. Christensen, *The Innovator's Dilemma* (Harvard Business School Press, Cambridge, 1997).

[2] Preparing for the Revolution: Information Technology and the Future of the University (Washington, D.C.: National Academies Press, 2003), www.nap.edu.

[3] Daniel E. Atkins (chair), (2003). *Revolutionizing Science and Engineering Through Cyberinfrastructure*, Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure. National Science Foundation, Washington, DC.