Introduction

What are the implications for graduate education of the following:

1. Imagine if the extraordinary advances in cognitive science, neuroscience, and learning theories actually began to be applied in educational practice, yielding significantly improved outcomes at lower cost. What would happen if some lower tier universities got religion and were able to offer demonstrably better educations? What would that do to their competing colleges and universities? Would the top tier emulate them?
2. Suppose the digital generation were to take control of their learning environments, demanding not only the highly interactive, collaborative learning experiences but the sophistication and emotional engagement of gaming technology and the convenience of other IT-based services.
3. If students vote with their feet (and thumbs) and their dollars, what changes would they demand? If courses based on game technology, excellent graphics, and pleasant surroundings (not 8am in a drafty hall) compete with current offerings, what changes would result.
4. Today the common thread of most university libraries is the presence of a Starbucks. What happens if the Google digitization project creates in every Starbucks all the world's libraries?
5. The globalizations of scientific activity, as new collaborations enabled by information and communication technology compete with traditional organizations such as the research university for the loyalty and participation of scholars. The evolution of global research communities, increasingly independent of traditional institutions such as universities or industry
6. Newly emerging scholarly communities that compete with and break apart the feudal hierarchy that has traditionally controlled research training (particularly doctoral and postdoctoral work), empowering young scholars and enabling greater access to scientific resources and opportunities for collaboration and engagement.
7. The impact of cyberinfrastructure on the "culture" of scientific activities and institutions, e.g., publication, collaboration, competition, travel, and the ability of participants to assume multiple roles (master, learner, observer) (leader, learner, lurker) in various scholarly communities, the increasing importance of creativity

relative to analysis as powerful new tools of investigation (e.g., simulation, massively pervasive sensor arrays) enabled by cyberinfrastructure appear.

8. At its most abstract, the "university" is a community of masters and scholars (*universitas magistorium et scholarium*), a school of universal learning that embraces every branch of knowledge and all possible means for making new investigations and thus advancing knowledge. These two characteristics, scholarly community and breadth of both intellectual topics and tools, have remained the core elements of the various forms taken by the university from medieval times (e.g., Paris and Bologna), through the Renaissance and Enlightenment, to today's research universities. We already see these elements appearing in new forms enabled by cyberinfrastructure, e.g., global, domain-specific communities of scholars detached from traditional institutions such as universities, and exceptionally broad digital collections of knowledge such as digital libraries or the archives of search engines such as Google. Could these be the precursors of a new form of the university, essentially appearing spontaneously out of the vacuum state of the cyberspace enabled by cyberinfrastructure?

The Context

We live in a time of great change, an increasingly global society, knitted together by pervasive communications and transportation technologies and driven by the exponential growth of new knowledge. It is a time of challenge and contradiction, as an ever-increasing human population threatens global sustainability; a global, knowledge-driven economy places a new premium on workforce skills through phenomena such as off-shoring; governments place increasing confidence in market forces to reflect public priorities even as new paradigms such as open-source technologies challenge conventional free-market philosophies; shifting geopolitical tensions driven by the great disparity in wealth and power about the globe, national security, and terrorism. Yet it is also a time of unusual opportunity and reason for optimism as these same technologies enable the formation of new communities and social institutions, better able to address the needs of our society.

Rapidly evolving digital technology, so-called cyberinfrastructure, has played a particularly important role both in expanding our capacity to generate, distribute, and apply knowledge. More precisely, cyberinfrastructure refers to infrastructure based

upon distributed computer, information, and communication technology. While certainly consisting of hardware and software, cyberinfrastructure also encompasses the people, organizations, and policies which support digital technology. This technology is evolving very rapidly, linking people, knowledge, and tools in new and profound ways, and driving rapid, unpredictable, and frequently disruptive change in existing social institutions. But since cyberinfrastructure can be used to enhance learning, creativity and innovation, intellectual span, and collaboration, it presents extraordinary opportunities as well as challenges to an increasingly knowledge-driven society.

Information technology changes the relationship between people and knowledge. And it is reshaping in profound ways knowledge-based institutions such as our colleges and universities.

- We can now use powerful computers and networks to deliver educational services to anyone, anyplace, anytime, no longer confined to the campus or the academic schedule.
- Technology is creating an open learning environment in which the student has evolved into an active learner and consumer of educational services.
- Faculty loyalty is shifting from campus communities and universities to scholarly communities distributed in cyberspace.
- The increasing demand for advanced education and research from a knowledge-driven society, the appearance of new for-profit competitors, and technological innovations are stimulating the growth of powerful market forces that could dramatically reshape the higher education enterprise.

In fact, some believe that the very future of the university, at least as we know it, is at risk:

Frank Rhodes: "I wonder at times if we are not like the dinosaurs, looking up at the sky at the approaching comet and wondering whether it has an implication for our future."

The ITFRU Project

It was just such concerns 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.

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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 ITFRU Project (Information Technology and the Future of the Research University) 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 a 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, and outreach); its organization, structure, management, and financing; and the impact on the broader higher education enterprise and the environment in which it functions.

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.

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 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*,[i] 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.

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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.[ii]

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 ("the IT-Forum") 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.

Education

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. (This was a theme we were to encounter again and again in our later workshops). The provosts believed that their universities needed 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.

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 their 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 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.

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. The students are forming learning communities on their own, using instant messaging, e-mail, and other IT-mediated communications technologies.

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.

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, by building peer groups of learners, and 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.

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.

Since we really don't "teach" graduate students how to teach anyway, one might well question whether digital technology will have much impact on this area. Yet here the challenges may be particular acute. After all, since we expect graduate students to learn the trade from their own experience as students, one might well doubt whether they will learn the new "tricks" of technology-based instruction from the old dogs of the "sage-on-the-stage" lecture paradigm. Even more formidable will be developing a generation of faculty equipped with the skills necessary to design and manage active learning environments.

Research

The National Science Foundation Blue Ribbon Advisory Panel on Cyberinfrastructure 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."[iii]

Clearly, cyberinfrastructure is not only reshaping but actually creating new paradigms for science and engineering research, training, and application. The availability of powerful new tools such as computer simulation, massive data

repositories, massively ubiquitous sensor arrays, and high-bandwidth communication are allowing scientists and engineers to shift their intellectual activities from the routine analysis of data to the creativity and imagination to ask entirely new questions. New paradigms are evolving for the sharing of scientific knowledge, such as the open source movement (Open Knowledge Initiative) and powerful search engines (Google). Globalization is a particularly important consequence of the new forms of scientific collaboration enabled by cyberinfrastructure, which is allowing scientific collaboration and investigation to become increasingly decoupled from traditional organizations (e.g., research universities and corporate R&D laboratories) as new communities for scholarly collaboration evolve.

Today's research problems are becoming increasingly complex, and their solution requires interdisciplinary teamwork. The training of new Ph.D.s currently is often too narrow intellectually, too campus centered, and certainly too long. The acceptance of overspecialization can result in a lack of both perspective and self-confidence. New Ph.D.s often believe themselves ill prepared to venture outside their specialty. This is due in part to the lack of serious requirements for breadth in the typical graduate curriculum. It is also due to the fact that there is little or no encouragement and a lot of implicit discouragement for one who wants to depart from the straight and narrow.

We have suggested that rather than stratifying our society, information technology will likely become a democratizing force in higher education. It will democratize learning by distributing learning opportunities far more broadly than our currently highly selective education system is capable of or inclined to do. Moreover, it will likely democratize scholarship as well by providing a far broader spectrum of institutions, scholars, and perhaps even lay citizens with access to the rich intellectual resources of our most prestigious institutions. Although this democratizing character may threaten both elite colleges and research universities, it may also be key to meeting the mass educational needs of our knowledge-driven society.

The Most Difficult Question of All…

Those of you in this audience know the good news-bad news character of digital technology. We overestimate the impact in the near term, because we implicitly assume

that the present will continue, simply at an accelerated pace, and fail to anticipate the disruptive technologies and killer apps that turn predictions topsy-turvy. Yet, we also know that far enough into the future, the exponential character of its evolution makes even the boldest predictions about digital technology come true.

This is the good news–and also the bad news: This stuff is just as disruptive as we predicted it to be! (Good News) And this stuff is just as disruptive as we predicted it to be! (Bad News)

To this end, the IT Forum is beginning to shift its attention from exploring the question of "How to save the university" to consider instead "How will research and learning occur in the digital age?"

This is another reason for this shift in emphasis. While university presidents are sometimes reluctant to speculate about the longer-term future of their institutions, our workshops found the provosts somewhat less inhibited? In fact, our discussions with provosts frequently covered a very broad range of very fundamental issues such as the mission, roles, values, and traditions of the university.

One of our IT Forum members, Susanne Lohmann, reminded the group that within a single generation after the Civil War period, American higher education changed essentially every one of its characteristics in a radical fashion:

- Evolving from the colonial colleges to the Humboldtian model of a research university.
- Empowering the faculty.
- Growing from institutions with hundreds to thousands of students
- Through the Land-Grant acts, creating the new paradigm of the engaged public university.
- Adding research and service to the mission of education (or, in many of the colonial colleges, socialization).

Everything that could change, in fact, did change.

The consensus in several of our workshops has been that we are well along in a similar period of dramatic change in higher education. In fact, some of our colleagues were even willing to put on the table the most disturbing question of all: Will the university, at least as we know it today, even exist a generation from now? Disturbing, perhaps. But certainly a question deserving of very careful consideration, at least by those responsible for leading and governing our institutions.

Some Final Remarks

So what might we anticipate as possible future forms of the university? The monastic character of the ivory tower is certainly lost forever. Although there are many important features of the campus environment that suggest that most universities will continue to exist as a place, at least for the near term, as digital technology makes it increasingly possible to emulate human interaction in all the sense with arbitrarily high fidelity, perhaps we should not bind teaching and scholarship too tightly to buildings and grounds.

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.

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.

For at least the near term, meaning a decade or less, we believe 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.

Put another way, 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.

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

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

[iii] 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.