# The Impact of Technology on Discovery and Learning in Research Universities

James J. Duderstadt
President Emeritus, University of Michigan

IX Glion Colloquium
June 5 – 9, 2013

Today, our world has entered a period of rapid and profound economic, social, and political transformation driven by knowledge and innovation. Educated people, the knowledge they produce, and the innovation and entrepreneurial skills they possess have become the keys to economic prosperity, public health, national security, and social well-being. It has become apparent that economic strength, prosperity, and social welfare in a global knowledge economy will demand a highly educated citizenry. It will also require institutions with the ability to discover new knowledge, to apply these discoveries, and transfer them to the marketplace through entrepreneurial activities.

Yet, the fundamental intellectual activities of discovery and learning that enable these goals are being transformed by the rapid evolution of information and communications technology. Although many technologies have transformed the course of human history, the pace and impact of digital information technology is unprecedented. In little more than half a century, we have moved from mammoth computer temples with the compute power of a digital wristwatch to an ecosystem of billions of microelectronic devices, linked together at nearly the speed of light, executing critical complex programs with astronomical quantities of data. Rapidly evolving digital technology, so-called *cyberinfrastructure*, consisting of hardware, software, people, and policies, has played a particularly important role, both in expanding our capacity to generate, distribute, and apply knowledge. (Atkins, 2003) It has become an indispensable platform for discovery, innovation, and learning. This technology is continuing to evolve 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.

Clearly, today cyberinfrastructure continues not only to reshape but actually create new paradigms for science and engineering research, training, and application in science and engineering and increasingly also in the humanities and arts. 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 enable them to ask entirely new questions. New paradigms are evolving for the sharing of scientific knowledge, such as the open knowledge movement and powerful search engines. Globalization is a particularly important consequence of the new forms of scientific collaboration enabled by cyberinfrastructure. Cyberinfrastructure 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.

New paradigms are rapidly emerging as well for learning and education, as well as innovation and professional practice such as open knowledge resources (e.g., Wikipedia, MIT's OpenCourseWare initiative, and Google Books), online education supported by social networking (e.g., Massively Open Online Courses or MOOCs), open learning initiatives (e.g., Carnegie Mellon's cognitive tutor technology), and immersive learning environments (including massively multiplayer gaming). The challenge for discovery and learning is to use cyberinfrastructure as a platform for enhancing knowledge communities and for expanding their scope and participation unconstrained by time and distance by stressing the interconnection between learning about, learning to do, and learning to be, eventually becoming a member of a community of practice. (Brown, 2000) To quote Arden Bement, former NSF Director, "We are entering a second revolution in information technology, one that may well usher in a new technological age that will dwarf, in sheer transformational scope and power, anything we have yet experienced in the current information age" (Bement, 2007).

## The Future of Digital Technology

### A Personal Observation

In the early 1970s, while I was working in the area of nuclear systems at

Lawrence Livermore National Laboratory, I was allocated daily computing time on their CDC 7600, then the fastest computer in the world at 10 MFLOPS (one million floating-point-operations-per-second, the standard unit for measuring computing speed). Today, my colleagues are running their simulations of nuclear reactors on the TITAN computer at Oak Ridge National Laboratory at a speed of 16 PFLOPS. Hence, over the past four decades, computation speeds have increased over a billion-fold. In fact, most characteristics of this technology are continuing to evolve exponentially at rates of 100 to 1,000 fold per decade. We are already developing our nuclear system computer software for the anticipated delivery of an exaFLOP supercomputer in the next five years, so the trend continues.

This is one of the big reasons for the continued surprises we get from the emergence of new applications–the Internet, social networking, big data, machine learning–appearing in unexpected ways at an ever faster pace. We have learned time and time again that it makes little sense to simply extrapolate the present into the future to predict or even understand the next "tech turn". These are not only highly disruptive technologies, but they are highly unpredictable. Ten years ago nobody would have imagined Google, Facebook, Twitter, etc., and today nobody really can predict what will be a dominant technology even five years ahead, much less ten!

Fortunately, universities have been able to adapt to such rapid technological change in the past because they have functioned as *loosely coupled adaptive systems* with academic units given not only the freedom, but also the encouragement, to experiment to try new things. It is at the level of academic units rather than the enterprise level where innovation and leadership will occur. Why? Because academic programs are driven by learning and discovery, by experimentation, by tolerance for failure, and by extraordinarily talented faculty, students, and particularly, staff. Most academic institutions have intentionally avoided the dangers of centralizing these activities and instead focused maintaining a highly adaptive academic culture.

## Moore's Law

Although most characteristics of cyberinfrastructure, e.g., processing power, data storage, and network bandwidth, continue to increase at an exponential pace described by Moore's law, various components of the technology do eventually encounter limits and saturation that require major technology shifts. For example, VLSI processors and memories are approaching the limits of miniaturization and hence processing speed. In the near term, devices are exploiting multiprocessor architectures, with dozens of processors on a single chip (and millions of processors in supercomputers). But other constraints, such as power requirements, will soon require new technologies such as DNA storage and quantum computing.

Similar evolution continues to occur in how information is processed. For example, companies such as Google and Amazon are built around data, analyzing and extracting information and knowledge from large data centers (or clouds). Here, scale truly matters, with increases of factors of ten in storage and processing speed regularly required and achieved to meet market requirements. Similarly, data concepts have shifted to larger, more abstract structures such as entitles, concepts, and knowledge, that require enormous increases in data storage and processing speed. They also require more sophisticated software for data processing to enable rapid searches for abstract concepts through petabytes of data.

The Human Interface

One of the most rapidly changing characteristics of this technology involves the human interface. Although we look back at the transition from text to image to video to 3D immersive displays, there are other characters such as mobility, size, and context that also change rapidly. For example, the development of software agents that rely on natural interactions such as speech and context awareness are already transforming both mobile phones (e.g., Apple's Siri) and interfaces with the physical world (e.g., Google's efforts to insert computing into eyeglasses to assist in context analysis). The use of intelligent agents or assistants (IBM's Watson) can make us look better than we really are by anticipating and completing tasks that are not fully defined, although this raises an interesting set of policy and legal issues since even the most intelligent agents can make mistakes because of faulty information or incorrect assumptions based on inaccurate data. The question of what intelligent agents do on your behalf and liability issues are unresolved questions. Similarly, there is great interest in the evolution of the Internet into a network of objects such as ubiquitous sensors, the rise of contextual data, and the ability to do predictive models of individual behavior. The need for accessibility raises the issue of digital inclusion in the broadest sense. How does one design technology to assist physically challenged individuals, aging populations, those with limited literacy skills, and, indeed, provide a global population of 10 billion with robust digital access.

Although the rapid evolution of information and communications technology is driving much of the change in the activities of the university, it is important to consider this from a much broader perspective, including legal issues (patents, copyright), policy (local, national, international), and social issues (access and accessibility, equity, interoperability, sustainability, and resilience). For example, students and faculty need appropriate technology scaffolding for their academic pursuits (e.g., cyberinfrastructure). But they also need a broader understanding of systems thinking in addition to domain-specific knowledge, the future potential and disruptive nature of this technology, and the paradigm shifts in learning and discovery it is likely to drive.

## The Next Big Paradigm Shift

So what are the early warning systems for the next major paradigm shifts? What does one look for? During the 1980s, a modest computer network, NSFnet, was developed to connect scientists to supercomputer centers, only to find that people did not want to use supercomputers but rather to communicate with one another. This led within a few years to the Internet, another technology that changed the world. Google spun out of the Page Rank search algorithm created by a Stanford research project to develop digital libraries. (Levy, 2011) Facebook was started even more modestly by a group of students seeking to digitize and distribute the picture book Harvard created for entering students. (Kirkpatrick, 2011).

So where do you look for these surprises? Do you look at the research labs on college campuses? Do you look at Harvard dormitories for what students are doing before they drop out? Do you try to spot the next Bill Gates, Mark Zuckerberg, or Larry Page? Do you have any tracking systems? Industry participants usually respond that they first sense such possibilities when activities characterized by hyper exponential growth break free of the campuses, e.g., the Internet, Google, and Facebook. Similarly, they look for interesting students and faculty members that they can break free of the campus culture. Their success model is based on what escapes rather than what stays inside academic institutions.

From industry's viewpoint, the elephant in the room is knowledge creation, not knowledge dissemination, which is the role of the research university. The challenge is to become more focused on knowledge creation, integration, synthesis, and dissemination, or perhaps more abstractly, DIKW: *data, information, knowledge, and wisdom*. One needs to use cyberinfrastructure together with tools that enhance creativity, and then broaden access through libraries, search tools, and push models in education.

As a framework, one can begin by observing that the fundamental activities of the university are organized into knowledge communities – those that engage with knowledge and discovery. (Brown, 2000) The extent to which the university facilitates knowledge communities should be the basis for its merit. Today, people can work together in four quadrants: same/different – time/place. One can build a rich connection between people, information, and tools. The work of these knowledge communities supported by a cyberinfrastructure platform can now be done in new workflows that go through space-time quadrants in different ways. Cyberinfrastructure now allows tools, data, experiments, and other assets to support online knowledge communities, making these functionally complete in any of the four quadrants, that is, with all the resources necessary to handle knowledge flow. Using the scaffolding of cyberinfrastructure, one can dramatically reduce constraints of distance and time. This creates a major disruption in how knowledge work is done, expanding significantly the degrees of freedom.

## Possibilities, Game-Changers, and Paradigm Shifts

### New Paradigms for Learning and Teaching

So, what are the opportunities presented by cyberinfrastructure for learning and teaching, for example, Massively Open Online Courses (MOOCs), cognitive tutor systems, or Carnegie Mellon's Open Learning Initiative. Some believe that today higher education is on the precipice of an era of extraordinary change as such disruptive technologies challenge the traditional paradigms of learning and discovery. (Friedman, 2011) They suggest that new technologies could swamp the university with a tsunami of cheap online courses from name-brand institutions, or adaptive learning using massive data gathered from thousands of students and subjected to sophisticated analytics, or even cognitive tutors that rapidly customize the learning environment for each student so they earn most deeply and efficiently, entirely without the involvement of faculty.

But are these really something new or rather simply old wine in new bottles? After all, millions of students have been using online learning for decades (estimated today to involve over one-third of current students in the United States). There are many highly developed models for online learning, including the UK Open University, the Western Governor's University in the United States, and the Apollo group's global system of for-profit universities. Adaptive learning has been used in Carnegie Mellon's cognitive tutor software for years in secondary schools and more recently in the Open Learning Initiative. Many of the buzzwords used to market these new technologies also have long established antecedents: Experiential learning? Think "laboratories" and "internships" and "practicums"…and even "summer jobs"! Flipped classrooms? Think "tutorials" and "seminars" and "studios". Massive markets of learners? Many American universities were providing free credit instruction to hundreds of thousands of learners as early as the 1950s through live television broadcasts!

Of course, today's MOOCs do have some new elements, aside from the massive markets they are able to build through the Internet and their current practice of free access. (Waldrop, 2013) They augment online broadcasts of canned lectures and automated grading of homework with social networks to provide teaching support through message boards and discussion groups of the students themselves. Their semi-synchronous structure, in which courses and exams are given at a specific time while progress is kept on track, allow them to augment online broadcast of canned lectures and automated grading of homework with social networks to provide free teaching assistants through message boards and discussion groups. Here one might think of MOOCs as a clever combination of UK's Open University (online education) and Wikipedia (crowd sourcing of knowledge)! Furthermore, MOOCs, like the far-more sophisticated Open Learning Initiative, are able to use data mining (analytics) to gather a large amount of information about student learning experiences. When combined with cognitive science, this provides a strong source of feedback for course improvement.

Certainly the MOOC paradigm is characterized by a powerful delivery mechanism. But it is just one model. It is much more important to focus on improving learning by integrating emerging technology with research about how people learn. There are also other models to explore and much richer collaboration opportunities to share. Through knowledge creation, we need to embrace new paradigms as a community. Automated assessment and evaluation could turn the whole education business upside down because we will have access to massive data sets that potentially will give us some insight in not how we deliver content but rather how people learn.

Of course, many of these efforts are driven by the exploding global needs for higher education that creates gigantic markets. For example, to meet the needs of its population, India would have to build thousands of new universities just to handle its current number of secondary school graduates. But here is where new paradigms such as MOOCs come in, since these can handle courses for 100,000 or more students at a time by using a combination of online and social networking technology. Of course, there remains the need for rigorous assessment of learning effectiveness, but some of the efforts to apply data mining and analytics to the massive data collected by these online efforts may be a key to evaluation.

What about the role of credentials? While there has been recent exploration of providing college credit for MOOCs on a highly selective basis, it is more likely that an alternative certificate or badge system will be used to certify that learning goals have been achieved. One might even consider micro-credentials with a time value, that is, a student would receive a certificate that would be valid until they take the next test. But students who might like a MOOC may be different than those who respond to tutor or that pedagogy or certain structure on content. Customization for individual need is required to meet huge opportunity space in this knowledge area. The learner is the customer. It is not just about the learning or how to push it out but rather how will they learn with this technology? How can this be structured to address different learning styles since good classroom teachers have this capacity to adapt teaching methods to the students?

It is likely that MOOCs are a disruptive technology, and that analytics on learning data holds considerable promise. But it is also very important to separate the fundamental character of a college education from the specific resources used to achieve that, e.g., courses and curricula, textbooks and course notes, faculty and laboratory staff, and, of course, the complex learning communities that exist only on university campuses. After all, MOOCs are marketed as courses, not as a college education. We must remember that the current university paradigm of students living on a university campus, completely immersed in an exciting intellectual and social physical environment and sophisticated learning communities, provides a very powerful form of learning and discovery. MOOCs are interesting, but they are far from the vibrant, immersive environment of a college education, at least as we understand it today. (Brown, 2000)

There is also a big difference between the perspective of the providers of MOOCs and the students who are their consumers. Right now, we are watching the providers figure out what they are going to do, with strong investments from the venture capital community and for-profit education providers suggesting that at least some people believe they might become very rich from these gigantic educational markets. Furthermore, today's MOOCs are aimed primarily at individuals, not communities. There is a huge challenge thinking about what they will mean in the university, and whether the second tier institutions can use off-the-shelf MOOC courses and do something with them to reduce cost or bring in new kinds of students. But there are many questions. What happens to faculty governance issues? What about copyright issues? Who owns these courses? Are all of the professors going away, replaced by

MOOC broadcasts from star teachers and using crowd sourcing to grade and answer questions?

Finally, we should remember that this new paradigm is being launched by several of the most elite and expensive private universities in America (e.g., Stanford, Harvard, and MIT) using both the Internet and social media as well as their powerful brand names to build mammoth markets for their MOOC companies (Udacity, Coursera, EdX) in an effort to eventually create new revenue streams to subsidize the rapidly rising costs of more traditional, highly expensive education on their own campuses. A related concern is that the intense media hype given these new learning paradigms has put enormous pressure on public colleges and universities from governing boards and state governments attempting to reduce the costs of college education, even at the sacrifice of educational equality. It would be tragic if technology-based paradigms such as MOOCs were to drive even greater inequities in higher education.

## New Paradigms for Research and Scholarship

### Is the Paradigm for Basic Research Really Changing?

Are the paradigms characterizing research and scholarship paradigms also shifting with emerging technologies? Certainly the language of research is changing to embrace concepts such as clouds, data mining, convergence, etc. If you subscribe to view that there is a paradigm shift from hypothesis-driven to data-correlation-driven discovery, then the culture of scientific and engineering discovery and innovation is changing as a result of access to data, computational technology, and social networks. We are going to need new models for sharing data, software, and resources such as computational technology

But is the way in which research is conducted changing? What about global competition? Is the world of facilities-intensive big science, such as high-energy physics , sustainable when it requires sending faculty and students to the only places capable of conducting the research (e.g., CERN), resulting in a list of authors longer than substance of the papers? Are we moving to a wiki world where crowd sourcing of amateurs becomes important for scientific research? How important is the role of research and scholarship within universities? Do we need to tweaking of tax laws so the translational research characterizing earlier paradigms, such as Bell Laboratories, begin to reappear as part of the knowledge ecosystem?

.

Universal Access to Knowledge and Learning

Ironically, while we generally think of cyberinfrastructure in terms such as terabit/sec networks and petaflop supercomputers, the most profound changes in our institutions may be driven not by the technology itself but rather by the philosophy of openness and access it enables– indeed, imposes–on its users. Of particular importance are efforts to adopt the philosophy of open source software development to create new opportunities for learning and scholarship for the world through *open educational resources* by putting previously restricted knowledge into the public domain and inviting others to join in both its use and development. (Atkins, 2007)

MIT led the way with its OpenCourseWare (OCW) initiative, placing the digital assets supporting almost 2,000 courses into the public domain on the Internet for the world to use. (Vest, 2004) Today, hundreds of universities have adopted the OCW paradigm to distribute their own learning assets to the world, with over 15,000 courses now available online. New resources, such as Apple's iTunes U, are providing global access to such open educational resources.

To this array of open educational resources should be added efforts to digitize massive quantities of printed material and make it available for search and eventual access. For example, the Google Book project is currently working with a number of leading libraries (26 at last count in 35 languages) around the world to digitize a substantial portion of their holdings (22 million volumes in 2013, with a goal of 30 million by 2020), making these available for full-text searches using Google's powerful internet search engines. (Google, 2004) A number of universities (84 thus far) have pooled their digital collections to create the Hathi Trust ("Hathi" means "elephant" in Hindi), adding over 400,000 books a month to form the nucleus (currently at 11 million books, with 3 million of these already open for full online access) of what could become a 21st century analog to the ancient Library of Alexandria. (HathiTrust, 2009; Kelly, 2006) While many copyright issues still need to be addressed, it is likely that these massive digitization efforts will be able to provide full text access to a significant fraction of the world's written materials to scholars and students throughout the world within a decade.

We should add into this array of ICT-based activities a few more elements: mobile communication, social computing, and immersive environments. We all know well the rapid propagation of mobile communications technology, with over 4 billion people today having cell-phone connectivity and 1.2 billion with broadband access. It is likely that within a decade the majority of the world's population will have some level of cell-phone connectivity, with many using advanced 3G and 4G technologies.

Finally, the availability of new learning resources, such as massively open online learning (MOOC) consortia (Udacity, Coursera, and EdX), cognitive AI-based tutor software (Carnegie Mellon's Open Learning Initiative), and immersive learning environments similar to those developed in the massively player gaming world (World of Warcraft and Second Life) are providing resources that not only open up learning opportunities for the world but furthermore suggest new learning paradigms that could radically challenge and change existing higher education paradigms.

What do we know about the effectiveness of these technology-based approaches? Where are the careful measurements of learning necessary to establish the value of such forms of pedagogy? Thus far, promoters have relied mostly on comparisons of performances by both conventional and online students on standard tests. The only serious measurements have been those that Ithaka has conduced on the learning by cognitive tutor software in a highly restricted environment. (Bowen, 2012)

Of course, it eventually comes back to the questions of "What is the most valuable form of learning that occurs in a university…and how does it occur?" Through formal curricula? Through engaging teachers? Through creating learning communities? After all, the graduate paradigm of *Universitas Magistrorum et Scholarium* involving the interaction of masters and scholars will be very hard to reproduce online…and least in a canned video format!!!

As William Bowen, former president of Princeton and the Mellon Foundation and a founder of Ithaka suggests, it is time to "Walk, Don't Run" toward the use of cyberlearning. We need lots of experimentation, including rigorous measurement of education–before we allow the technology tsunami to sweep over us! (Bowen, 2013)

## Change and the University

History provides many examples of the ability of the university to adapt to change. Five centuries ago some suggested that the medieval university would not survive the printing press since people could learn by reading books rather than attending lectures. More recently, a decade ago, MIT's OpenCourseWare initiative to place the digital assets for all of their courses, 2,000 in number, in the public domain stimulated similar fears this would sink the universities and create a $2 trillion for-profit education economy. But once again, universities floated through this technology turn without major change.

In fact, the university today looks very much like it has for decades–indeed, centuries--in the case of many ancient European universities. It is still organized into academic and professional disciplines; it still bases its educational programs on the traditional undergraduate, graduate, and professional discipline curricula; and the university is still governed, managed, and led much as it has been for ages. We can always explain this by falling back on that famous quote of Clark Kerr: "About 85 institutions in the Western World established by 1520 still exist in recognizable forms, with similar functions and with unbroken histories, including the Catholic Church, the Parliaments of the Isle of Man, of Iceland, and of Great Britain, several Swiss cantons, and…70 universities." (Kerr, 2001)

But if one looks more closely at the core activities of students and faculty, the changes over the past decade have been profound indeed. (Duderstadt, 2003) The scholarly activities of the faculty have become heavily dependent upon digital technology–rather cyberinfrastructure–whether in the sciences, humanities, arts, or professions. Although faculties still seek face-to-face discussions with colleagues, these have become the booster shot for far more frequent interactions over the Internet. Most faculty members rarely visit the library anymore, preferring to access digital resources through powerful and efficient search engines. Some have even ceased publishing in favor of the increasingly ubiquitous digital preprint or blog route. Student life and learning are also changing rapidly, as students bring onto campus with them the skills of the net generation for applying this rapidly evolving technology to their own interests, forming social groups through social networking technology (Facebook, Twitter), role playing (gaming), accessing web-based services, and inquiry-based learning, despite the insistence of their professors that they jump through the hoops of the traditional classroom paradigm.

In one sense, it is amazing that the university has been able to adapt to these extraordinary transformations of its most fundamental activities, learning and scholarship, with its organization and structure largely intact. Here one might be inclined to observe that technological change tends to evolve much more rapidly than social change, suggesting that a social institution such as the university that has lasted a millennium is unlikely to change on the timescales of tech turns, although social institutions such as corporations have learned the hard way that failure to keep pace can lead to extinction. Yet, while social institutions may respond more slowly to technological change, when they do so, it is frequently with quite abrupt and unpredictable consequences, e.g., "punctuated evolution".

It could also be that the revolution in higher education is well underway, at least with the early adopters, and simply not sensed or recognized yet by the body of the institutions within which the changes are occurring. Universities are extraordinarily adaptable organizations, tolerating enormous redundancy and diversity. It could be that the information technology revolution is more of a tsunami that universities can float through rather than a rogue wave that will swamp them.

Admittedly, it is also the case that futurists have a habit of overestimating the impact of new technologies in the near term and underestimating them over the longer term. There is a natural tendency to implicitly assume that the present will continue, just 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 the evolution of Moore's Law technologies such as info-, bio-, and nano- technology makes almost any scenario possible. (Kurzweil, 2005)

However, here we should take heart with a note of reassurance provided by Frank Rhodes in his Declaration for the Millennium crafted in the III Glion Colloquium:

"For a thousand years, the university has benefited our civilization as a learning community where both the young and the experienced could acquire not only knowledge and skills, but the values and discipline of the educated mind. It has defended and propagated our cultural and intellectual heritage, while challenging our norms and beliefs. It has produced the leaders of our governments, commerce, and professions. It has both created and applied new knowledge to serve our society. And it has done so while preserving those values and principles so essential to academic learning: the freedom of inquiry, an openness to new ideas, a commitment to rigorous study, and a love of learning.

There seems little doubt that these roles will continue to be needed by our civilization. There is little doubt as well that the university, in some form, will be needed to provide them. The university of the twenty-first century may be as different from today's institutions as the research university is from the colonial college. But its form and its continued evolution will be a consequence of transformations necessary to provide its ancient values and contributions to a changing world. " (Rhodes, 1999)

Acknowledgements: Much of the material for this paper was provided by a workshop at the University of Michigan sponsored by the National Science Foundation in October of 2012 to assess the impact of rapidly evolving information and communications technology (i.e., cyberinfrastructure) on the activities of discovery, learning, and

innovation. This workshop convened an unusually diverse group of thought leaders from multiple disciplines and venues to consider the changing nature of learning and discovery in broad terms, spanning learning at all levels and discovery for all forms including research, development, innovation, invention, design, and creativity. The complete discussion sessions of this workshop were captured using multiple HD camera and sound technology and can be found at: http://specular.dmc.dc.umich.edu/Atkins/

References

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

Atkins, Daniel E., John Seely Brown and Allen L Hammond. *External Review of the Hewlett Foundation's Open Educational Resources (OER) Program: Achievements, Challenges, and Opportunities.* Menlo Park, CA: Hewlett Foundation, February, 2007.

Bement, A. L. *"Cyberinfrastructure: The Second Revolution".* Chronicle of Higher Education, January, 2007.

Borgman, Christine L. (chair). *Fostering Learning in the Networked World: The Cyberlearning Opportunity and Challenge*. Report of the NSF Task Force on Cyberlearning. Washington, D.C.: National Science Foundation, 2008.

Bowen, William G. *"Walk Deliberately, Don't Run, Toward Online Education".* Chronicle of Higher Education. March 25, 2013; See also William G. Bowen, *Higher Education in the Digital Age*. Princeton, NJ: Princeton University Press, 2013.

Bowen, William G., Matthew M. Chingos, Kelly A. Lack, and Thomas I. Nygren. *Interactive Learning Online at Public Universities: Evidence from Randomized Trials.* Ithaka, May 22, 2012, available on the ITHAKA website: http://www.sr.ithaka.org

Brown, John Seely and Paul Duguid. *The Social Life of Information*. Cambridge, MA: Harvard Business School Press, 2000; see also Douglas Thomas and John Seely Brown. *A New Culture of Learning.* San Francisco, CA: Thomas and Brown, 2011.

Duderstadt, James J. (chair). *Preparing for the Revolution: Information Technology and the Future of the Research University.* Washington, D.C.: National Academy Press, 2003; see also Duderstadt, James J., Daniel E. Atkins, Douglas Van Houweling. *Higher Education in the Digital Age: Technology Issues and Strategies for American Colleges and Universities*. Westport, CT: American Council on Education and Praeger Publishers, 2002.

Google Books, http://books.google.com/, 2011

HathiTrust, http://www.hathitrust.org/, 2011

Kirkpatrick, David. *The Facebook Effect: The Inside Story of the Company That Is Connecting the World*. New York: Simon & Schuster, 2011.

Levy, Stephen. *In the Plex: How Google Thinks, Works, and Shapes Our Lives*. New York: Simon & Schuster, 2011.

Kelly, Kevin. *"Scan This Book!"*. New York Times Sunday Magazine, May 14, 2006.

Kerr, Clark. *The Uses of the University*. 5th Edition. Cambridge: Harvard University Press, 2001.

Kurzweil, Ray. *The Singularity Is Near: When Humans Transcend Biology*. New York, NY: Viking Penguin, 2005.

Rhodes, Frank H.T. *"The Glion Declaration: The University at the Millennium".* in Challenges Facing Higher Education at the Millennium. Phoenix, AZ: American Council on Education and Oryx Press, 1999.

Vest, Charles M. *"Why MIT Decided to Give Away All Its Course Materials via the Internet"*. Chronicle of Higher Education, January 30, 2004.

Waldrop, M. Mitchell. *"Campus 2.0"*. Nature, Vol. 495, March 14, 2013