A Half-Century of Technological Change

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At Michigan I currently direct a research center, the Millennium Project, concerned with the impact of technology on our society, our communities, our institutions, and our planet. Hence it is amusing to look back to our years at Yale to see how changing technology has affected our lives over the past half century.

Actually, many of our activities really haven't been changed very much. Cars and planes aren't much faster. Our roads and buildings and cities look pretty much the same. We still depend on energy from oil, gas, and coal (unfortunately). Health care? Some progress in life expectancy, but the major impact of biomedical research is still ahead? We did make it to the moon, but then we stopped. We still haven't blown ourselves up with atomic energy, but it also hasn't made the deserts bloom yet. And I should confess that the impact of my early work on testing nuclear-powered rockets designed for a manned mission to Mars or advanced forms of nuclear power such as laser-driven thermonuclear fusion remain only a remote possibility for the distant future.

But before we conclude that technological change over the past 50 years is no big deal, let me offer another personal perspective. While at Yale I had the opportunity to run a couple of programs on their huge ($2.5 million) IBM 7090 computer. This machine was able to achieve an amazing 40,000 flops (floating point operations a second, the way that one measures computer speeds). Impressive? Not so much, since ten years later I was working on a CDC 7600 at Lawrence Livermore Laboratory that was a thousand times faster at 10 megaflops. Today, I am part of a nuclear research project that utilizes the Titan supercomputer at Oak Ridge National Laboratory, currently the fastest in the world at 20 million-billion flops (20 petaflops), and we are creatin software to run on the next generation of exaflop machines (i.e., a billion-billion flops) that we expect will be available later this decade. What is the point of this history? Over the past 50 years, the power of computer technology has increased by a one trillion-fold! That is, the characteristics of computing hardware–speed, memory,

bandwidth–have been and are likely to continue increasing by factors of 100 to 1,000 every decade!

This is one of the big reasons for the continued surprises we get from the emergence of new applications based on information and communications technology–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, and Twitter, and today nobody really can predict what will be a dominant technology even five years ahead, much less ten!

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 in expanding our capacity to generate, distribute, and apply knowledge. 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.

To illustrate, let me provide two further personal experiences. At Michigan we were very good at building networks linking together computers, so when the federal government put out a request-for-proposal in 1985 to build a national network to link scientists to supercomputers, we joined with IBM and MCI to design and build such a network for the National Science Foundation. We were fortunate to select a communication protocol developed by the defense industry (TCP-IP) that allowed our network to expand very rapidly, increasing at a rate of 10% a month! As this network became larger and larger, the federal

government asked us to add in other federal networks to create an "internetwork". Perhaps you have already guessed where I'm headed. This UM-IBM-MCI project became the Internet, which we managed until 1993 when industry began to take it over.

But I'm not through yet. In the mid 1990s, we received another grant from the federal government to develop a digital library. (We already had the experience of developing the JSTOR library for the Mellon Foundation.) Among the students working on this project was a computer engineering major named Larry Page. (I'll bet you're already ahead of me again.) Page went on to graduate school at Stanford (also part of the same digital library project), where he and Sergey Brin developed the Page-Rank algorithm that was the key to the Google search engine. In 2004 Page returned to Michigan with the offer to have Google digitize our entire library (all 8 million volumes), which would become the nucleus of a major book search service, Google Books, now providing Internet search access to over 20 million volumes.

Today Michigan has joined 50 other universities (including Yale) to take a step beyond Google Books. We have pooled our collections of digitized volumes to create a massive digital library, named the HathiTrust ("hathi" means elephant in Hindi), with the goal of eventually providing full access to these materials, including the conduct of data analytics on the collection. While there are a few wrinkles we have yet to iron out with copyright law and the courts, today the HathiTrust is already the largest digital library in the world with over 13 million volumes, including 3.4 million we have already opened for full text access.

So what's next? Who knows? As we look even further into an unknowable future, the possibilities and uncertainties become even more challenging. Attempting to predict the future is always a hazardous activity. We generally overestimate change in the near term and underestimate it for the longer term, in part because we usually tend to extrapolate what we know today into a future that becomes increasingly beyond our imagination. It is very difficult to peer over the horizon and imagine a future characterized by the possibility that anyone with even a modest Internet or cellular phone connection will have access to all of the recorded knowledge of our civilization along with

ubiquitous learning opportunities and access to network-based communities throughout the world.

Imagine still further the linking together of billions of people with limitless access to knowledge and learning tools enabled by a rapidly evolving scaffolding of cyberinfrastructure, which increases in power one-hundred to one thousand-fold every decade. This hive-like culture will not only challenge existing social institutions–corporations, universities, nation states–that have depended upon the constraints of space, time, laws, and monopoly. It will enable the spontaneous emergence of new social structures as yet unimagined–just think of the early denizens of the Internet such as Google, Facebook, Wikipedia, …and, unfortunately, Al Qaeda. In fact, we may be on the threshold of the emergence of a new form of civilization, as billions of world citizens interact together, unconstrained by today's monopolies on knowledge or learning opportunities.

Perhaps this, then, is the most exciting vision for the future of knowledge and learning organizations such as the university, no longer constrained by space, time, monopoly, or archaic laws, but rather responsive to the needs of a global, knowledge society and unleashed by technology to empower and serve all of humankind. And all of this is likely to happen during the lives of today's students–in fact, much of it will occur during the golden years of the Yale Class of 1964.