CHAPTER 2

Technological Innovation in the 21st Century

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THE INNOVATION IMPERATIVE

The early years of the 21st century have found the U.S., Europe and Asia increasingly committed to technology-based innovation as the road to economic prosperity. Every CEO has had a catchphrase to this effect on his or her tongue. Etsuhiko Shoyama of Hitachi says "Ceaselessly Innovate", and Sam Palmisano of IBM says "Innovate or Abdicate".

Many speakers and observers have quoted a poem attributed to Richard Hodgetts:

Every morning in Africa a gazelle wakes up.
It knows it must outrun the fastest lion or it
Will be killed.
Every morning in Africa a lion wakes up.
It knows it must outrun the slowest gazelle
Or it will starve.
It doesn't matter whether you are a lion or a
Gazelle — when the sun comes up, you'd
Better be running.

Now all of this connotes that the world is in a hurry, and for good reason when it comes to technology, its development, marketing, acceptance, and economic and social impact. After the automobile was introduced as a consumer product in the early part of the 20th century, it took 55 years to create and penetrate markets such that 25% of the U.S. population had one in their household. In those days, 55 years was essentially a lifetime. Another society-changing consumer innovation was the telephone. It took 35 years to reach

25% of the U.S. population, and 35 years was essentially a working lifetime. By the time the personal computer came along, it took about 16 years until 25% of the U.S. population had one, and it took only 8 years for the World Wide Web to achieve this penetration (Council on Competitiveness, 2005).

So when we say that the impact of technology is accelerating, we are speaking truth. But the key word here is "impact". The automobile, telephone, personal computer and World Wide Web are prime examples of world-changing, empowering technologies that drove economic advancement. There also is an interesting evolution from the automobile that initially had its primary impact in the United States to the World Wide Web that had almost instantaneous *global* impact. The clear progression is from national and slow to global and fast. Furthermore, there also is a distinct path from big and mechanical to small and electronic.

These observations get to the heart of the innovation imperative. From the perspective of a company or an industry, the implications are very clear. Most companies set goals such as 20-40% of their business to come from products developed in the last two or three years. The specific goal and speed of introduction naturally depend on the product sector. The stakes are high: fall behind in innovations that continuously improve your product or expand your product range, and you are out of business.

But there is a deeper level of importance to innovation and speed. When I was a graduate student in about 1965, one of my friends was studying for a Ph.D. in electrical engineering. One day his professor said to him: "I think that in the future, telecommunications and computing are going to merge somehow. You should think about this." When you read this, please put your mind in the frame of 1965, and you will see that this was a radical prediction. My friend took that advice and he is a very successful person today.

In other words, combining telecommunications and computing was not just an incremental improvement, it was the deeper kind of innovation — one that changed society by empowering and enabling all manner of things. Fast forward to today; our world is under enormous financial stress. As we move beyond this crisis, we must rebuild an economy based on the production of real goods and services that are of real value. The Holy Grail we seek is the next major enabling and empowering technology — the 21st century equivalent of Information Technology. Somewhere the spark of this innovation is forming in someone's mind. Innovation is the process by which it will be developed, made real, and brought to the marketplace. I have no idea what the next major enabling technology will be or where it will be spawned, but there are some things we can learn about the environment that may encourage its development.

To initiate an exploration of innovation's future, let me suggest four facts, three consequences, and one principle. I will add to this list an irony.

The four facts are: People everywhere in the world are smart and capable; science and technology advance relentlessly; globalization is a dominating reality; and the Internet and World Wide Web are democratizing forces.

The three consequences are: Individuals must innovate; companies must innovate; and nations and regions must innovate.

The principle is: competition drives excellence and innovation.

And finally, the irony is that in the 21st century cooperation and competition reinforce each other.

THE U.S. INNOVATION SYSTEM 1945-2009: A BRIEF HISTORY

There is value in understanding where we have come from, as long as we don't assume that what worked in the past will, without modification or replacement, work in the future. With that caveat, let me trace the outline of America's innovation system since World War II. During most of this period, the U.S. had a comparative advantage because it developed a strong S&T base and coupled it to a free-market economy that was in turn built on a base of democracy in a diverse society. But there also was a clear policy basis that enabled scientific and technological advancements.

In November 1944, President Franklin Roosevelt wrote a letter to Vannevar Bush, who was then on leave from MIT serving as head of the Office of Scientific Research and Development (OSRD). His role was to mobilize U.S. science and industry to serve the war effort. In his letter, Roosevelt stated that U.S. science had contributed mightily to a pending Allied victory. He then asked Bush to form a committee and tell him how the U.S. science community could work in peacetime to secure the nation's economic vitality, health and security, just as it had advanced national interests in the war. Nine months later, Bush submitted his now famous report, *Science — the Endless Frontier* (Bush, 1945). This report made four fundamental recommendations:

1. Universities should be the primary national infrastructure for doing basic research;
2. Federal dollars supporting university research should do double duty by procuring research results and simultaneously supporting the education of the next generation of engineers, scientists and doctors;
3. Research grants should be awarded to university investigators on the basis of technical and intellectual merit; and
4. A National Science Foundation should be established to further these ends.

The Bush recommendations may be "old hat" today, but this was a profound and rather radical vision at the time. However, as we look at this from the vantage point of the early 21st century, we should note two implicit assumptions about economic development. The Bush model is *linear* and *laissez-faire*. It is linear in that it more or less assumes that there is a straightforward progression from basic research to applied research to product development and then to the marketing of goods and services. Basic research would be done in universities. Applied research would be done in some mix of universities and industry. Product development and marketing would be the sole province of industry. It was *laissez-faire* in the sense that it assumed that industry would scan the research results from universities, select the important results and then commercialize them as products or services. Neither government nor industry would be expected to select research topics or guide research programs.

What emerged from the Bush approach was the U.S. Innovation System that created new knowledge and technology through research, educated young men and women to understand and create this new knowledge and technology, and moved it to market as new products, processes and services. This system was an enormous success from any perspective. Economists generally believe that about half of U.S. economic growth since the War was due to technological innovation, much of which originated in research universities.

During the period from 1945 to roughly 1985, America's public and private research universities grew to excel and set the world standard. American companies dominated many product domains. Large corporations were dominant, especially those based on mass production. Many large companies also developed outstanding central research laboratories that attracted outstanding university graduates, conducted outstanding pure and applied research, and contributed to the "S&T commons" through the technical literature and professional meetings. Then two tectonic shifts occurred in the 1980s and, 90s.

Suddenly, Japanese companies dominated the consumer-manufacturing sector, and U.S. companies could not effectively compete with them. Japanese advances in quality, throughput and product cycle times were astonishing. Indeed, the Japanese Total Quality Movement was the major innovation in the world in the 1980s. It changed everything. It is important to note that this was not a purely technological innovation; rather, it was about organization, discipline, quantitative and statistical approaches, and social motivation.

U.S. and European corporations responded through painful, fundamental and permanent transformations. Downsizing, process management and quality control became central. But most relevant to this history of innovation, corporate R&D was dramatically changed and merged with product development. Many companies emerged strong and globally competitive, but the U.S. Innovation System had changed.

During the latter stages of this transformation, a second tectonic change occurred; in some sense it happened just in time. Namely, American entrepreneurship expanded explosively, driven by information technology made possible by the microprocessor revolution and the Internet. The rapid advance of biotechnology also played a major role.

The broad thrust of U.S. corporate innovation and R&D seems to have changed on a decadal time scale. The 1970s was the golden age of central corporate research laboratories. Absorbing and transforming R&D into product development dominated the 1980s, as already mentioned. In the 1990s, companies became concerned that although they were now competitive and adept at incremental improvement, they were not generating sufficient amounts of basic innovation, so they began to acquire it by purchasing high-tech start-up companies that often had been spawned by research universities. In the first decade of the 21st century, a more globally integrated open innovation system began to form. The linear model implicit in the Bush vision was breaking down and being replaced by a more complex, faster, nonlinear regime.

There was a similar decadal evolution of university research and education that paralleled this. The 1970s was the golden age of the "engineering science revolution", an approach that emerged largely from the wartime work at MIT's Radiation Laboratory and the Manhattan Project. A base of science supported a new way of teaching and practising engineering. This movement from engineering as an empirical, "handbook" activity to one based on design and development from first scientific principles was essential to the new "high technology" world. In the 1980s, many universities began to respond to the manufacturing crisis by moving design, manufacturing, and computer science to centre stage, and by introducing joint management/engineering programs. The 1990s saw an explosion of university emphasis on life sciences, more interdisciplinary work, and more direct engagement in use-inspired research and commercialization. This continued into the early 21st century.

The nature of the challenges facing humankind in the early 21st century will lead, as has been noted, to more use-inspired research in universities. A word about this concept is in order. One of the great technological achievements of the 20th century was the development of the transistor at Bell Labs. Bell Labs in those days had one of the most impressive staffs of engineers and physical scientists ever assembled. They made many contributions to the basic understanding of the physical world. The technical staff had much opportunity to think and explore important problems and to publish their work in the open literature. Because of this flexible and open environment, an "urban legend" has grown up that the transistor resulted from unfettered basic research. The fact is that it was the result of a carefully planned and executed R&D program. The people who contributed to it were often doing very basic work, but there was a specific goal of creating a solid state device to replace the vacuum tube. This is a prime example of use-inspired basic research.

In 1997, the late Donald Stokes of Princeton University explored how the flow of knowledge to product had changed from the linear, *laissez-faire* approach of Vannevar Bush's *Science — the Endless Frontier* (Stokes, 1997). He found a very useful framework to help answer this question: a two-dimensional plot in which the vertical axis displays the answer to the question: "Is the research motivated by the quest for fundamental understanding of the natural world?" and the horizontal axis displays the answer to the question: "Is the research motivated by consideration of use of the results?" Stokes thereby referred to pure basic research as residing in the "Bohr Quadrant" because it is motivated only by the desire to understand nature. He considered research to reside in the "Edison Quadrant" if only a practical result is sought. The "Pasteur Quadrant" contains research that has the dual motivation of increasing fundamental knowledge and being driven toward a practical application. This, of course, refers to Louis Pasteur's seminal scientific work that developed fundamental knowledge of microbiology in order to reduce disease.

Many of the challenges we face today regarding energy, climate, sustainability, clean water, food, medicine and healthcare must both advance the state of knowledge of physical and biological science, but also drive toward technological solutions. Indeed, the term *technological innovation* refers to an extension of use-inspired research; it is an activity that either discovers or designs new technologies and systems and moves them along a pathway to practical applications or introduction to the marketplace.

INNOVATION AND GLOBALIZATION

Most observers seem to agree that innovation is the key to many advances in human welfare, and certainly to economic vitality. For much of modern history, innovation was largely a local or national activity, building or improving factories, distribution systems and businesses. Indeed, prior to World War II nations prospered largely on the basis of geography, natural resources, capable labourers and military might. This local or national centricity has long since passed from the scene in most developed nations. There are many reasons for this, but among them certainly are the roles of inexpensive long-distance travel and shipping, the global flow of information via the Internet and World Wide Web, and the geographic spread of talent and knowledge generation. From the business perspective, labour costs, intellectual property policy and especially tax policy should be added to these factors. The whole innovation scene is changing rapidly and is not well understood, but its relentless globalization is very clear.

Two indispensable input variables for innovation are a workforce well educated in engineering and science and expenditures on R&D. These are not sufficient conditions, but certainly are necessary. Even a cursory look at the available data indicates that the distribution of engineering and science degrees around the world has changed dramatically during the last two decades. The headline indicator is the rise of engineers educated in China, and across Asia in general. For examples, in 1983, the U.S., Japan and China each graduated approximately 75,000 bachelor-level engineers. By 2002, the U.S. production of bachelor-level engineers dropped to about 60,000 while the production in Japan rose to 100,000 engineers, and the production in China rose to 250,000. The trend can be expressed in an even more meaningful way by the fact that today about 4.5% of U.S. college and university graduates earn degrees in engineering, about 12% of European university graduates are engineers, and across Asia about 20% are engineering majors (National Science Foundation, 2008). This is a colossal redistribution of the talent base required for innovation.

There has been a similar rapid shift in the global distribution of R&D expenditures by both government and industry. The fact is that the total annual expenditures on R&D are now spread almost evenly around the developed world, with about one third each in North America, Europe, and Asia.

This spread of the potential for innovation has been amplified by the deployment of the Internet and the World Wide Web. As Thomas Friedman famously wrote: “The world is flat,” and globalization has “accidentally made Beijing, Bangalore and Bethesda next-door neighbors,” with many jobs being “just a mouse click away”. (Friedman, 2006). Although Friedman’s analysis woke many from their lethargy about the modern world, this is only part of the story, although a very important part. Others have argued that it is not true that location no longer matters, because the power of regional innovation clusters such as Silicon Valley and Route 128 is still important. These local clusters often are enabled by the proximity of small companies and corporate laboratories to research-intensive universities.

The quest to understand the evolution and probable future course of innovation has spawned considerable scholarly study and publication during the last several years. Henry Chesborough, then at the Harvard Business School and now at the University of California at Berkeley, introduced the term *open innovation* to characterize what goes on in most large companies today, i.e. to be competitive they must integrate the best ideas no matter where they originate, in other countries, in other companies or laboratories, and often even in competing organizations. This is part, but not all of the reason that corporations are opening R&D laboratories in many different countries to be close to and able to tap into organizations worldwide (Chesborough, 2006). And every industry works day-to-day in fear of not recognizing and grasping “disruptive technologies”, the game-changing ideas and technologies that Clayton Christensen has so clearly expounded in his 1997 book, *The Innovators Dilemma* (Christensen, 1997).

Related ideas are developed in John Hagel and John Seeley Brown’s analysis, *The Only Sustainable Edge*, although they place great emphasis on the development of deep disciplinary capabilities within corporations as well as good connectivity with other companies and organizations. They also point to the need for constant learning across networked enterprises (Hagel & Seely Brown, 2005). I also note the research of Michael Piore and Richard Lester, which points out two important institutional capabilities, *analysis* and *interpretation*. In this context, *analysis* refers to the ability to form a rational, discrete, quantitative basis for decisions. This is essential for innovative product development and productivity gains. But they find that interpretation is the heart of true innovation. Here *interpretation* encompasses exploiting ambiguity, imagining alternative pathways and endpoints, and the creative removal of constraints (Piore & Lester, 2004).

Judy Estrin, former Chief Technical Officer of Cisco and highly successful entrepreneur, has recently assessed the *innovation ecosystem* of the United States and concluded that there are numerous indications that it is declining. She finds an increasing focus on the near term and an attenuation of free-spirited openness that defined America. Her analysis delineates the nature and characteristics of organizations and leaders that innovate well. She urges a return to long-term, adventurous perspectives that can enable technology and business to interact to produce and market new goods and services in the global economy (Estrin, 2009).

The public perception of innovation is often focused on small, flashy IT-related technologies or web tools. However, as implied in the preceding discussion, innovation is necessary at all scales. In the United States and elsewhere, we are faced with a need to innovate on a massive scale to deal with the production, storage and distribution of electrical energy. This is a very complex problem because of the variety of technologies that need to be improved, eliminated or discovered, and because of the scale of deployment and infrastructure required. One must add to this the huge corporate investments in existing infrastructure and the major role that must be played by government policy and investment at the federal, state and local levels. Some have called for a national technology roadmap to the next generation energy system. But, in my view, this problem is too large and complex, and too rich in opportunities for new game-changing discoveries and developments, to begin mapping a detailed technology pathway. Weiss and Bonvillian have recently written a book, *Structuring an Energy Technology Revolution*, in which they propose a roadmap not directly to specific technologies, but rather a roadmap for innovation that recognizes both the uncharted nature of technology and the government roles in policy-making and research (Weiss & Bonvillian, 2009).

Finally, it is clear that a variety of modes of global cooperation will be needed to address innovation associated with energy. The fundamental reasons are that the geopolitical stakes in energy resources and distribution are extremely high, and that the underlying issues of climate change and sustainability are global.

INNOVATION: WHAT IS NEXT?

As noted above, the core of the industrial innovation system in the U.S. has changed substantially about every decade. In the 1970s, central corporate research laboratories dominated; in the 1980s, corporate R&D was transformed and absorbed into a new style of product development in response to the challenge of Japanese consumer manufacturing; in the 1990s, large companies acquired innovation by buying start-up companies often spun out from research universities; and in the early 2000s, open innovation has begun to play a major role.

Several things suggest that we may see another shift in the U.S. innovation system:

1. The scientific basis of new technologies will increasingly come from the life sciences and information technology;
2. Macro-scale systems challenges, especially energy, will drive innovation in the coming decade;
3. Some believe that the venture capital system is becoming too risk averse and may not be appropriate to the large-scale issues that badly need innovation;
4. Globalization of R&D investments, education and high-quality workforce will continue apace;
5. Economic growth probably requires a new enabling technology to play a role analogous to that played by IT and the World Wide Web during the last decade; and
6. We will need some truly transformative breakthroughs and disruptive new technologies in order to address many of the global grand challenges such as energy, healthcare and security.

I do not know what the future actually holds, but I will briefly address four factors that may be involved in the next stage of innovation: evolution of the current system, education, prizes, and large-scale web interaction.

There is an almost universal movement to improve education in science, mathematics and engineering at the primary and secondary level. Asian countries in particular have set contemporary standards in this regard in order to strengthen the base for technology, innovation and 21st-century economic competition. It is likely that information technology also will play a role in increasing the knowledge base, reasoning abilities and scientific skill sets of young people. But innovation requires more than this important base; it requires abilities of imagination, synthesis, open-ended problem solving, and the elusive quality of creativity.

Much of future innovation in the U.S. context will likely continue to be carried out through the informal and loosely coupled system of universities, companies and governments that has dominated since the end of World War II. But this system may be augmented or readjusted to tackle large-scale 21st century challenges. For example, a 2004 U.S. National Academy of Engineering report chaired by James Duderstadt suggested the formation of a set of *Discovery Innovation Institutes* to be located on the campuses of research-intensive universities (National Academy of Engineering, 2005). They would be intended to conduct engineering research and innovation at a larger scale than is typical for universities today and that would have direct linkages and responsibility to industries. These continuous linkages to relevant industries would provide guidance to use-inspired research and would increase the efficiency and effectiveness of movement of new ideas, discoveries and technologies into the commercial sector. Such institutes would be especially suitable to complex, large-scale and long-lived challenges such as energy.

In higher education there are many experiments underway to foster and enhance innovation capacity and new modes of thought. *Olin College of Engineering*, outside Boston, has operated now for seven years with a nontraditional, design-oriented curriculum and an organizational structure without the usual disciplines. Finland is constructing an entire new, large-scale institution, *Aalto University*, which will combine technology, economics, and art and design. It will be established in 2010 by merging programs from three existing universities, but it will afford an opportunity to rethink and reformat curricula and build a community of scholars with a new collective perspective. Singapore is establishing a new university in partnership with MIT that will also be focused heavily on science, engineering, information systems and architecture with a special emphasis on the role of design, broadly defined. Opening in 2011, it is explicitly intended to be part of a new ecosystem for producing innovations and new products.

In California, *Singularity University* is the working name of a joint effort by NASA, Google and several leading thinkers such as Ray Kurzweil to bring together students from the emerging disciplines of nanotechnology, biotechnology, and information technology. The purpose will be to cross educate them in these fields and prepare them to attack the great challenges of our times. The working name is an allusion to Kurzweil's theories expounded in his book, *The Singularity is Near* (Kurzweil, 2005). The hypothesis of this book is that many new technologies will follow exponential growth models like the well-known Moore's Law, and therefore change far more rapidly and transformatively than our traditionally linear thinking leads us to expect, thereby rapidly giving us the tools to solve huge societal problems. Whether or not this somewhat Utopian view is correct, this approach will provide a rich tool set and experience base for 21st-century innovators.

Another intriguing attempt to unstick the innovation system to achieve large goals is the work of the X-Prize Foundation. In 1996, the Foundation offered the $10 million Ansari X-Prize to the first private, i.e. non-governmental, group to achieve human space flight, rigorously defined. This prize was won in 2004 by *SpaceShipOne* designed by Burt Rutan and financed by Paul Allen. But the point here is that not only was the goal achieved, but the financial prize money was highly leveraged by the various competing groups, thereby accelerating investment of both financial and intellectual resources to push technology forward.

The X-Prize Foundation, chaired by Peter Diamandis, is expanding this concept to several other areas of technological challenge that require levels of innovation that do not appear to be forthcoming from the usual industrial or governmental systems. Their goal is to spur innovation to solve problems and leverage financial and intellectual resources of contest entrants to move technology forward. The best known of their extant programs is the Progressive Automotive X-Prize to build an automobile that achieves 100 mpg or equivalent. The prize-winning automobile must pass all U.S. highway safety standards, carry four passengers, have an acceptable manufacturing plan and have consumer appeal. 111 entrants have qualified for the competition.

There are many emerging, web-based platforms for developing and using the collective input of large numbers of people to forge new ideas, solve problems and, in a broad sense, innovate. An obvious example is *Wikipedia*, and the creation of many special purpose wikis following its example. The U.S. intelligence community has even applied this new collective tool to the production of intelligence estimates. *Roseta.org* is a website that enables thousands of people around the world to play a massive computer game the real purpose of which is to use their collective brain power to solve very complex problems of protein folding and bimolecular design.

A direct use of IT to enable innovation is the IBM *InnovationJam* conducted by IBM to innovate in its organization and product line. First held as a virtual discussion among its worldwide employee base, it is now conducted not only with IBM employees, but with thought leaders in many other companies and organizations. A topic is set for consideration, and participants can log into the conversation over a multi-day period. There is a rigorous process for narrowing down lines of thought and specific suggestions until a finite set of actionable recommendations is established. IBM indicates that its 2008 Jam lasted 90 hours and involved 90,000 log-ins and 32,000 posts. Participants came from 1,000 companies across 20 industries.

CONCLUSION

The U.S. Innovation System has been highly successful for over 60 years and it has been replicated in many countries around the world. This has helped fuel a global rise in economic power and quality of life. But, as a result of this globalization, the system must now be transformed in ways that are not yet clear. Such transformation is demanded by the changing base of science that supports technology, and by the scale and importance of such worldwide challenges as food, water, energy, healthcare, climate change and security. This paper has presented a sampling of the experiments and thinking that are beginning to drive transformations in national and global innovation ecosystems.

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