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Dimensions of innovation in a technology-intensive economy

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The following essay is based on a Keynote Address to the OECD "High Level Meeting of the Committee for Scientific and Technology Policy," Oslo, March 4, 2008, on the topic "Adjusting Policy to New Dimensions in Science, Technology and Innovation." The objective of the talk was to point out the difficulty of linking specific policies to specific measures of successful innovation, while nevertheless identifying broad policy characteristics that foster innovation.

Innovation is a defining human activity. Why it should now be a topic of the greatest interest to policymakers deserves some explanation. Precursors can be seen in an interest in the conditions for promoting "invention" that first appeared well before the industrial revolution, particularly in England, and was an important theme in the rise of America's economic strength through the nineteenth century. Innovation, by almost any definition has been associated with American economic culture for more than two centuries. What is different now? What are the special conditions that have reawakened interest in innovation, and what can we learn from them to enhance this fundamental human activity?

The explosive pace of nineteenth-century innovation, particularly in the United States and Great Britain, continued into the twentieth despite the debilitating impact of global warfare and associated large-scale economic and social disruption in the first half-century. But wars and economic depression took their toll, arguably slowing the application of extraordinary scientific discoveries that began at the turn of the century. As World War II ended, widely disparate patterns of industrial development disadvantaged all but a few nations—primarily the wartime antagonists—in the subsequent cold war period of growing technical innovation. The superpowers emerged from the war convinced of the need for state-supported technical innovation in the name of national security. Arms races, space races, and ideologically based geopolitical competition engendered remarkable innovations through policies that gave little attention to market forces, much too little in the case of centrally planned economies. As the cold war ended, however, the innovation landscape had already begun to rearrange itself in response to four decades of uneasy but relatively stable world-wide economic conditions, fed by a combination of wartime technology and

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cold war-enhanced innovations funded particularly by the United States, Germany , and Japan. New market-oriented economies emerged in the "Asian Tigers" to seize opportunities created by the rapidly developing information technology, falling transportation costs, and generally cheap energy. The demise of the Soviet Union released new political and economic forces whose effect seems to have been a further rapid globalization of technical capability, leading journalist Tom Friedman to observe famously in 2005 that, when it comes to economic competitiveness, *The World Is Flat*.

As the twenty-first century dawned, the former superpowers struggled to reorient priorities from cold war national security to economic competitiveness. All the older developed nations faced a new reality in which the same forces that powered intense globalization and competition a century earlier were once again in play, but in a vastly expanded international field. From a broad historical perspective, the emphasis on innovation for economic competitiveness is old news. The world is shaking off a near century-long geopolitical pathology that distorted the natural evolution of economic competition among nations, and now we are returning to what looks very much like nineteenth-century competitive conditions. Two features, however, are genuinely new: the number of national players—particularly the hugely populated Asian countries—and the revolution in information technology that is as profound in its effect on world economic conditions as the development of navigation in the sixteenth century or the introduction of powered machinery in the nineteenth. Innovation is just as important for national economic competitiveness today as it was more than a century ago, but globalization and the information revolution add a complexity that perhaps justifies an evolution if not a revolution in innovation policy.

The strongly technical flavor of the information revolution is one of several leading factors in the tendency today to link innovation to science through technology. Others include the widely shared hope that urgent societal problems such as environmental and health impacts of continued population growth may be solved or mitigated by science-driven technologies. It is well to keep in mind, however, that innovation is not necessarily a technical —nor technology a scientific—phenomenon. Linking science, technology, and innovation into an overall policy framework may suggest that we know more about how these activities are related than we really do. This very common linkage implicitly conveys a now discredited linear progression from scientific research to technology creation to innovative products. More nuanced pictures break these complex activities down into components that interact with each other in a multi-dimensional socio-technological-economic network. One analysis of this sort, Donald Stokes' now classic *Pasteur's Quadrant,* offers two dimensions—knowledge-inspired and use-inspired—which intersect in "Pasteur's Quadrant" of use-inspired basic research. More than two dimensions are probably needed to capture the complex modes of research and their interactions.

That technical innovation can be independent of science is amply demonstrated by the history of machinery for textile production in the eighteenth century. The advanced state of patent and copyright law in England compared with other countries gave strong incentives to English inventors and investors, but the newly emerging physical sciences had little impact. Indeed, the first practical weaving machine (patented 1785) was invented by Edmund Cartwright, a minister of the Church of England, poet and book reviewer, who wrote "As I had never before turned my thoughts to anything mechanical, either in theory or in practice, nor had even seen a loom at work, or knew anything of its construction, you will readily suppose that my first loom must have been a most rude piece of machinery." He was motivated by a chance conversation in a public house where a textile expert remarked that no one could ever build a practical weaving machine. According to his own account, Cartwright was inspired by an exhibition in London of “an automaton figure which played at chess.” But clearly Cartwright’s mind was prepared by his formal education, which included mathematics among the usual classical subjects.

While England’s intellectual property laws were important to these innovations, so was the tradition of weaving in Western England that owed much to the displacement of a large population of textile workers from France following the revocation of the Edict of Nantes in 1685. As their industry grew, the means of production changed, not, at first, because of machinery, but because of innovations in the organization of work. The factory system emerged along with, and slightly ahead of, the early machines. It is worth mentioning that American efforts to match the quality of English machine-woven goods failed repeatedly until an experienced English textile plant manager, Samuel Slater, immigrated in 1789, bringing details of the perfected machinery with him. England, of course, had strong laws forbidding transfer of this technology beyond its borders, and Slater had left the country surreptitiously. Industrial espionage, intellectual property theft, and vigorous patent litigation were constant features of the industrial revolution, as they are today.

I mean these tales from history to illustrate components of the complex innovation ecology that are familiar to us today: an effective legal regime of intellectual property protection, an immigration policy that welcomes skilled workers, availability of investment capital, attention to the organization and management of work, and the prospect of profit from one’s ingenuity. These are not exactly science policies, and they are not entirely technology policies. They are innovation policies, and they were clearly important factors in the early lead established by both America and Great Britain in the industrialization of the nations that dominated global trade and manufacturing by the end of the nineteenth century.

Science did eventually become an important source of inspiration and guidance to new technologies that supported broad innovation. Among technical innovators at the turn of the century those best prepared to benefit from advanced science had been educated in Europe. American science grew rapidly during the twentieth century, but remained weak in theoretical subjects that would become so important during and after World War II. This weakness was repaired by an influx of brilliant scientists from Europe during the middle third of the century, propelled by a dreadful intolerance not unlike that which drove France’s textile workers to England two and a half centuries earlier.

Science feeds technology in two different modes: it delivers novel empirically-rooted phenomena that might lead to a technology platform that supports broad innovations, and it provides theoretical tools and methods that assist engineering analysis and design. The discovery and development of quantum mechanics in the interval between the world wars made it possible to trace the origin (if not the detailed understanding) of nearly all technically important physical phenomena up to that time *and thereafter*. This aspect of completeness in the relevant physical sciences is not widely appreciated, but that is what makes it possible to direct “basic” research into areas likely to be important in applications. It is possible today to identify areas of “basic” science in which investigations are likely to produce socially relevant results. This is what makes “Pasteur’s Quadrant” a real option for guiding national investments in research. Many scientists complain that “directed basic research” is an oxymoron because no one can know in advance what useful thing might be discovered in a laboratory. That is true in a more narrow sense than scientists usually admit. Surely no one expected that monatomic layers of graphene could be manufactured by peeling with Scotch Tape, a 2004 observation that won its discoverers a Nobel prize in 2010. But scientists knew thin layers of carbon would likely have technical applications. The research may have been "curiosity driven," but the researchers did not choose graphene randomly for their subject. They were arguably working in Pasteur's Quadrant despite their disregard of particular applications.

What about the "pure" research (Bohr's Quadrant)? Does work on cosmology or string theory have any relevance for innovation? Bohr himself, a founding father of quantum mechanics, deployed his remarkable theory of atomic structure to elucidate the eminently useful periodic table of chemical elements. That was in 1921. Today we know quantum theory is the most well-verified physical theory ever constructed, and no one expects its predictions of human scale phenomena will fail in the future. The frontiers of size and energy where cosmology and string theory lie are far beyond any phenomenon of human relevance. And yet, our ability to probe these frontiers is limited by technology. Two things are interesting about innovative technologies for basic research. First, the drivers of technology at the frontiers are not the same as those societal necessities that are the typical mothers of invention. Direct attacks on any problem are likely to lead to incremental advances. Research at the technology-limited frontier of "pure" science can produce "out of the box" advances unlike anything motivated directly by practical problems. The second interesting thing is that basic science attracts very bright young people whose passion for discovery is uncannily powerful. The combination of "out of the box" technical needs and exceptionally motivated innovators can lead to profoundly novel innovations.

In the 1990s particle physicists at Columbia University struggled to calculate implications of a theory of strong nuclear forces (QCD) that presents formidable computational challenges. Existing computer architectures were too inefficient, so they designed a microprocessor specifically for "lattice gauge calculations." When they consulted IBM engineers to help optimize the design, the engineers saw in it the possibility of an entirely new and broadly useful architecture that they rapidly incorporated in a new generation of computers. In 2004 the new machine, "Blue Gene/L," recovered the "world's fastest supercomputer" title from Japan's NEC "Earth Simulator" that had been introduced with much fanfare only 2 years before. And it was a particle physicist at CERN who famously created an approach to using the Internet, the World Wide Web, that solved a technical need, but also transformed the Internet from a specialist tool to an extraordinary technology platform that has supported a new universe of innovations.

Necessity is said to be the mother of invention, but in all human societies "necessity" is a mix of culturally conditioned perceptions and the actual physical necessities of life. The concept of need, of what is wanted, is the ultimate driver of markets and an essential dimension of innovation. And as the example of the World Wide Web shows, need is very difficult to identify before it reveals itself in a mass movement. Today, the generation of perceived need is itself a matter of innovation. Innovation has this chicken-and-egg quality that makes it extremely hard to analyze. We all know of visionaries who conceive of a society totally transformed by their invention, and who are bitter that the world has not embraced their idea. Sometimes we think of them as crackpots, or simply unrealistic about what it takes to change the world. We practical people necessarily view the world through the filter of what exists and fail to anticipate disruptive change. Nearly always we are surprised by the rapid acceptance of a transformative idea. If we truly want to encourage innovation through government policies, we are going to have to come to grips with this deep unpredictability of the mass acceptance of a new concept. Works analyzing this phenomenon are widely popular under titles like *The Tipping Point* by Malcolm Gladwell or more recently the book by N.N. Taleb called *The Black Swan,* among others.

The innovations of interest to us here are those that become integrated into economies. What causes them to be adopted depends on their ability to satisfy some perceived need by consumers, and that perception may be an artifact of marketing, or fashion, or cultural inertia, or ignorance. Some of the largest and most profitable industries in the developed world—entertainment, automobiles, clothing and fashion accessories, health products, children's toys, grownups' toys!—depend on perceptions of need that go far beyond the utilitarian and are notoriously difficult to predict. And yet, these industries clearly depend on sophisticated and rapidly advancing technologies to compete in the marketplace. But they do not depend *only* upon technology. Technologies are part of the environment for innovation, or in a popular and very appropriate metaphor—part of the *innovation ecology*.

This complexity of innovation and its ecology is conveyed in Chapter One of a currently popular best-seller in the U.S. called *"Innovation Nation"* by the American innovation guru, John Kao, formerly on the faculty of the Harvard Business School:

> "I define it [innovation]," writes Kao, "as the ability of individuals, companies, and entire nations to continuously create their desired future. Innovation depends on harvesting knowledge from a range of disciplines besides science and technology, among them design, social science, and the arts. And it is exemplified by more than just products; services, experiences, and processes can be innovative as well. The work of entrepreneurs, scientists, and software geeks alike contributes to innovation. It is also about the middlemen who know how to realize value from ideas. Innovation flows from shifts in mind-set that can generate new business models, recognize new opportunities, and weave innovations throughout the fabric of society. It is about new ways of doing and seeing things as much as it is about the breakthrough idea."

This is not your standard OECD-type definition. Gurus, of course, do not have to worry about leading indicators and predictive measures of policy success. Nevertheless some policy guidance can be drawn from this high level "definition," and I will do so later.

The first lesson to be drawn from these examples is that the *structural* aspects of "science, technology, and innovation" are imperfectly defined, complex, and poorly understood. There is still much work to do to identify measures, develop models, and test them against actual experience before we can say we really know what it takes to foster innovation. There is a second lesson about the *temporal* aspects: all three of these complex activities are changing with time. Science of course always changes through the accumulation of knowledge, but it also changes through revolutions in its theoretical structure, through its ever-improving technology, and through its evolving sociology. Technology has its own intrinsic time scales, both long and short as it exploits the available science and builds out infrastructure like roads and power grids that enable a host of short-lived applications. Today, the pace of change in both science and technology is strongly impacted by the rapidly changing information technology.

An important contributor to the unpredictable temporal quality of innovation is the increasing role of market forces in making technology accessible. Technology today often flows from research and development laboratories but the ability of technology to influence both science and innovation depends strongly on its *commercial* adoption. Commercial-scale manufacturing drives down the costs of technology so it can be exploited in an ever-broadening range of applications by an ever-broadening community of innovators. The mass market for precision electro-mechanical devices like cameras, printers, and disk drives is the basis for new scientific instrumentation and also for further generations of products that integrate hundreds of existing components in new devices and business models like the Apple iPod and video games, not to mention improvements in old products like cars and telephones. Innovation is changing too as it expands its scope beyond individual products to include all or parts of systems such as supply chains, and inventory control, as in the Wal-Mart phenomenon. Apple's iPod does not stand alone; it is integrated with iTunes software and novel arrangements with media providers.

With one exception, however, technology changes more slowly than it appears because we encounter basic technology platforms in a wide variety of relatively short-lived products. Technology is like a language that innovators use to express concepts in the form of products and business models that serve (and sometimes create) a variety of needs, some of which fluctuate with fashion. The exception to the illusion of rapid technology change is the pace of information technology, which is no illusion. It has fulfilled Moore's Law for more than half a century, and it is a remarkable historical anomaly arising from the systematic exploitation of the understanding of the behavior of microscopic matter following the discovery of quantum mechanics. The pace would be much less without a continually evolving market for the succession of smaller and higher capacity products. It is not at all clear that the market demand will continue to support the increasingly expensive investment in fabrication equipment for each new step up the exponential curve of Moore's Law. The science is probably available to allow many more capacity doublings if markets can sustain them.

I worry about the psychological impact of the rapid advance of information technology. I believe it has created unrealistic expectations about all technologies and has encouraged a somewhat casual attitude among policy makers toward the capability of science and technology to deliver solutions to difficult social problems. This is certainly true of what may be the greatest technical challenge of all time—the delivery of energy to large developed and developing populations without adding greenhouse gases to the atmosphere. The challenge of sustainable energy technology is much more difficult than many people currently seem to appreciate. I am afraid that time will make this clear.

Structural complexities and the intrinsic dynamism of science and technology pose challenges to policy makers, but they seem almost manageable compared with the challenges posed by extrinsic forces. Among these are the complex processes of globalization and the impact of global economic development on the environment. The latter, expressed quite generally through the concept of "sustainability" is likely to be a component of much twenty-first-century innovation policy. Measures of development, competitiveness, and innovation need to include sustainability dimensions to be realistic over the long run. Development policies that destroy economically important environmental systems, contribute to harmful global change, and undermine the natural resource basis of the economy are bad policies. Sustainability is now an international issue because the scale of development and the globalization of economies have environmental and natural resource implications that transcend national borders.

From the policy point of view, globalization is a not a new phenomenon. Science has been globalized for centuries and we ought to be studying it more closely as a model for effective responses to the globalization of our economies. What is striking about science is the strong imperative to share ideas through every conceivable channel to the widest possible audience. If you had to name one chief characteristic of science, it would be empiricism. If you had to name two, the other would be open communication of data and ideas. The power of open communication in science cannot be overestimated. It has established, uniquely among human endeavors, an absolute global standard. And it effectively recruits talent from every part of the globe to labor at the science frontiers. The result has been an extraordinary legacy of understanding of the phenomena that shape our existence. Science is the ultimate example of an open innovation system.

Science practice has received much attention from philosophers, social scientists, and historians during the past half-century, and some of what has been learned holds valuable lessons for policy-makers. It is fascinating to me how quickly countries that provide avenues to advanced education are able to participate in world science. The barriers to a small but productive scientific activity appear to be quite low and whether or not a country participates in science appears to be discretionary. A small scientific establishment, however, will not have significant direct economic impact. Its value at early stages of development is indirect, bringing higher performance standards, international recognition, and peer role models for a wider population. A science program of any size is also a link to the rich intellectual resources of the world scientific and technical communities. The indirect benefit of basic scientific research to a developing country far exceeds its direct benefit, and policy needs to recognize this. It is counterproductive to base support for science in such countries on a hoped-for direct economic stimulus through science-driven technical products. Small country science programs can, however, feed relevant technical solutions to regional issues such as public health and poor agricultural practices in the face of inadequate logistical infrastructure.

Keeping in mind that the innovation ecology includes far more than science and technology, it should be obvious that within a small national economy, innovation can thrive on a very small indigenous science and technology base. But innovators, like scientists, do require access to technical information and ideas. Consequently, policies favorable to innovation will create access to education and encourage free communication with the world technical community. Anything that encourages awareness of the marketplace and all its actors on every scale will encourage innovation.

This brings me back to John Kao's definition of innovation. His vision of "the ability of individuals, companies, and entire nations to continuously create their desired future" implies conditions that create that ability, including most importantly educational opportunity. The notion that "innovation depends on harvesting knowledge from a range of disciplines besides science and technology" implies that innovators must know enough to recognize useful knowledge when they see it, and that they have access to knowledge sources across a spectrum that ranges from news media and the Internet to technical and trade conferences. If innovation truly "flows from shifts in mind-set that can generate new business models, recognize new opportunities, and weave innovations throughout the fabric of society," then the fabric of society must be somewhat loose-knit to accommodate the new ideas. Innovation is about risk and change, and deep forces in every society resist both of these. A striking feature of the U.S. innovation ecology is the positive attitude toward failure, an attitude that encourages risk-taking and entrepreneurship.

All this gives us some insight into what policies we need to encourage innovation. Innovation policy is broader than science and technology policy, but the latter must be consistent with the former to produce a healthy innovation ecology. Innovation requires a predictable social structure, an open marketplace, and a business culture amenable to risk and change. It certainly requires an educational infrastructure that produces people with a global awareness and sufficient technical literacy to harvest the fruits of current technology. What innovation does not require is the creation by governments of a system that defines, regulates, or even rewards innovation except through the marketplace or in response to evident success. Some regulation of new products and new ideas is required to protect public health and environmental quality, but innovation needs lots of freedom. Innovative ideas that do not work out should be allowed to die so the innovation community can learn from the experience and replace the failed attempt with something better.

Do we understand innovation well enough to develop policy for it? If the policy addresses very general infrastructure issues such as education, economic and political stability and the like, the answer is perhaps. If we want to measure the impact of specific programs on innovation, the answer is no. Studies of innovation are at an early stage where anecdotal information and case studies, similar to John Kao's book—or the books on *Business Week*'s top ten list of innovation titles—are probably the most useful tools for policy makers.

I have been urging increased attention to what I call the science of science policy—the systematic quantitative study of the subset of our economy called science and technology—including the construction and validation of micro- and macro-economic models for science and technology activity. International organizations, and particularly OECD, have been valuable players in this enterprise, and can do much to encourage deeper knowledge of the innovation ecology and thus provide better tools for policy makers. The deep effort OECD is now making to gather global information about innovation and its ecology is a welcome and valuable enterprise that must continue over a long period of time to be successful. Eventually we may learn enough to create reliable indicators by which we can judge the health of our global innovation ecosystem. For now, we should have confidence in the insights gained from centuries of experience with innovation. We know it requires a critical mass of broadly educated individuals interacting in a relatively stable and open socio-economic environment that encourages open communication and entrepreneurialism. All the apparatus of intellectual property protection, government regulation for public and environmental health and sustainability, and access to capital are part of this environment that are targets of ongoing public policy. How each of these parts contributes to the ultimate set of innovation indicators is likely to be different among the multitude of different niches in the rich and changing global ecology of human behavior.