

# *Nanoscience and Nanotechnology: Assessing the Nature of Innovation in These Fields*

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*Sociologists of science and others have long been interested in how advances in science come about, and their potential social and economic impacts. Developments in nanoscience and nanotechnology will provide social scientists with a unique opportunity to explore how scientific activities form de novo. Additionally, scientists will have the opportunity to examine the factors that drive science and technology in certain directions by considering how different models of innovation may explain how the topography of the knowledge-based economy is being shaped by radically new approaches to science.*

Nanoscience and nanotechnology will soon revolutionize science and industry. These fields enable scientists to create organic and inorganic matter on an atom-by-atom or molecule-by-molecule basis. The application of nanoscience has the potential to transform medicine, biotechnology, agriculture, manufacturing, materials science, aerospace, information technology, and telecommunications, to name just a few examples (Drexler, 1987).

In the United States, the National Nanotechnology Initiative (NNI) was established in 2000 to examine ways to create the knowledge base needed to fully exploit technological innovations arising from nanoscience. The U.S. government allocated \$423 million for this purpose during fiscal year 2001. Headed by the National Science Foundation, the NNI has invested in more than 600 projects and involves 2,500 faculty and university students. Several other countries around the world have started to make similar kinds of investments.<sup>1</sup> Because nanotechnology is a powerfully transformative technology, it is critical to understand where this technology is coming from and where it is going.

## **What Is Nanotechnology?**

Nanotechnology is an umbrella term for a wide range of technologies. Nanotechnology is expected to flow from discoveries in nanoscience. It is important to stress initially that nanoscience is not just another step toward miniaturization. It represents a convergence of quantum physics, molecular biology, computer science, chemistry, and engineering. Innovations arising from nanoscience are likely to be commercialized as greater control over atom-by-atom and molecule-by-molecule construction improves. Although nanotechnology is in its infancy, the principles behind nanoscience are becoming more universally understood and accepted.

Nanoscience is about the creation and manipulation of information. For example, a perfect crystal has very little information content, since its structure can be described concisely with a short string of bits to list the coordinates of silicon atoms to form a unit, and some more bits to indicate how the pattern can be repeated to form the crystal. Like biotechnology, nanoscience is the product of advanced information processing and management. The potential applications of nanotechnology are staggering (see Table 1).

Nanoscience represents a revolution in constructing devices with atomic precision (Crandell, 1996). One nanometer is one billionth of a meter (approximately 80,000 times as smaller as a human hair). Through a comprehensive study of the behavior of matter at the nanoscale, scientists are exploring ways to gain greater control over matter. Just as computers analyze and distribute data in binary format (0,1), nanotechnology involves constructing new materials (both organic and inorganic) by treating atoms and molecules as building blocks.

**Table 1. A Sample of Applications Expected to Emerge From Advances in Nanoscience**

Environmental	Remediate contaminated soil and water Reduce use of raw materials through improvements in manufacturing Rebuild the stratospheric ozone layer with the assistance of nanobots
Medical	Improve the delivery of drugs Develop techniques in nanosurgery Repair defective DNA Improve diagnostic procedures
Electronic	Develop molecular circuit boards Improve storage of data Develop molecular computers
Materials	Increase the strength of industrially valuable fibers Replicate valuable products (e.g., food, diamonds) Improve the quality and reliability of metals and plastics Manufacture "smart" materials

### How Can We Understand the Nature of These Innovations and Their Diffusion?

Nanoscience and developments in nanotechnology are expensive and require cooperation between universities, governments, and industry. Ahluwalia (1994) refers to such projects as "megascience." Megascience projects are defined as those undertaken primarily for the production of knowledge. They require formal management structures and resources that cannot be provided by a single agency, firm, or perhaps even country (examples include the Human Genome Project, ITER's ([www.iter.org](http://www.iter.org)) experimental tokamak fusion reactor, and synchrotron facilities including the Canadian Light Source project in Saskatoon, Saskatchewan, Canada).

The emergence of new science-based innovations has renewed concerns about how megascience projects are funded and how innovations from them get diffused. Not too long ago, the linear model of innovation dominated. Traditionally, knowledge transfer within innovation processes is considered a one-way flow of scientific or technological knowledge from academic research to industrial development and commercialization via hardware products or via oral or written communication. A necessary condition for the realization of knowledge transfer is the appropriate and effective interaction between knowledge supplier (university) and knowledge user (industry). Since the late 1970s, the existence of a communication gap be-

tween university and industry has increasingly been blamed for causing a lack of innovation capacity. Although the linear model is still widespread, especially in policy discourse, in recent literature there is broad consensus that it is inadequate. Flinterman, Teclemariam-Meshab, and Bunders (in press) identify from the literature the following deficiencies in the linear model:

- The role of demand in the marketplace is often given scant attention (Myers & Marquis, 1969).
- The central process of innovation is not science but design, and the assumption that basic research drives innovation is flawed (Kline & Rosenberg, 1986).
- There is an artificial distinction between basic and applied research (Stokes, 1997).
- It is incorrectly assumed that universities and industry are the only players. Several other actors play important roles in innovation processes, such as government (Leydesdorff & Etzkowitz, 1996), investors (Coehoorn, 1995), and end users (Bobrowski, 2000; Bunders, Broerse, & Zweekhorst, 1999; von Hippel, 1988).

Kline and Rosenberg (1986) criticized the linear model and launched the so-called chain-linked model of innovation processes. In this model, the "central chain of innovation" begins with design and moves toward development and production to marketing. Each step is linked together via feedback loops and all are side-linked to research. It is assumed that scientific research is not a source of inventive ideas but is used to solve problems along the chain of innovation. Science profits directly and indirectly from the products of innovative activities such as the tools and instruments made available by technology (Kline & Rosenberg, 1986).

Stokes (1997) introduced an alternative innovation model in his book *Pasteur's Quadrant*. This model rejects the traditional distinction made between basic and applied research. Stokes outlines how basic science could be oriented toward improving simultaneously an understanding of fundamental principles and stimulating improvements in technology by formalizing the links between science and technology. Named after the famous microbiologist Pasteur, this approach recognizes how Pasteur promoted a basic understanding of science while providing practical applications.

Another innovation model is the “triple helix” of Leydesdorff (2000) and Leydesdorff and Etzkowitz (1996). This model focuses on the overlay of communications and interactions between the three institutional spheres (three helices) of industry, university, and government. Each sphere produces its own knowledge, engages in marketplace activity, and attempts to control external influences. Through information exchange and shared expertise, internal transformations in each of the helices facilitate the generation of new ideas and stimulate innovation. The boundaries between public-private, science-technology, and university-industry are porous and in flux. Shaping these relations is increasingly a subject of science and technology policy at different levels. The triple-helix thesis is a recursive model of how institutions respond to various kinds of collaboration.

The last type of innovation model I would like to mention is called “national systems of innovation” (Niosi, 2000). A national system of innovation has been defined by Lundvall (1992) as “the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge . . . either located within or rooted inside the borders of a nation state” (p. 2). Such a system creates, stores, and transfers information, knowledge, skills, and artifacts related to technologies and innovations. Although scholars and policy makers apply different definitions and perspectives to this concept, in general the basic premise is that understanding the linkages between actors involved in innovation is central to improving technology performance (Organization for Economic Cooperation and Development, 1996). To conclude, innovation systems are characteristics of the nation-state (Nelson, 1993). However, they are being supplemented by regional and multinational systems in many parts of world (Kohler-Koch, 1993).

Knowledge generation seems to be shifting in this era of globalization. This shift becomes worthy of analysis because knowledge itself has become the mechanism by which wealth is generated (Bell, 1980). New forms of knowledge generation do not build on strong institutional frameworks but on bodies of knowledge that selectively combine in new programs and are mission driven. This mode of knowledge production is oriented toward the configuration of knowledge rather than its discovery and takes an inherently interdisciplinary approach to problem solving. Gibbons et al. (1994) call this mode II knowledge production (mode I being disciplinary). This contrasts with the “endless frontier” metaphor that suggested that

discipline-based science created ideas and opportunities that would naturally be taken up for direct economic development (Bush, 1945).

Etzkowitz (1994) suggests that we are moving into a new environment for innovation in which universities play a much stronger role. Consequently, we will need to better understand triple-helix dynamics and assess whether this model still applies or has merged somehow with the national systems of innovation approach. Langford, Langford, and Burch (1997) argue that triple-helix interactions in science are not entirely new. However, the smooth development of these relations was “denatured” by the rapid growth of universities and the scientific establishment following World War II. This ruptured the networking among players. There are also cultural differences between universities and industry in how science is done. The value system of academic science is strongly influenced by the approach to management and access to facilities (Ziman, 1994). This value system is summarized by the acronym CUDOS: communalism, universalism, disinterestedness, originality, and skepticism. Ziman (1994) suggests that this be contrasted with the norms for industrial research with the acronym PLACE: proprietary, local, authoritarian, commissioned, and expert. Not only do such differences make the triple helix a complex relationship to manage, they also introduce ethical and management dimensions into the equation, which brings issues such as academic freedom, autonomy, and corporate interference in university affairs into the limelight. Commenting on the complex relations between pharmaceutical companies, governmental regulatory bodies, and universities, Lewis et al. (2001) state, “Some bargains are Faustian, and some horses are Trojan. Dance carefully with the porcupine, and know in advance the price of intimacy” (p. 785).

Ethical questions about triple-helix relations are hardly novel, but they are certain to arise with transformative technologies such as nanotechnology. Some contend that institutional accommodations to new relationships with private companies have affected universities, bringing significant changes in university values and practices (Webster & Etzkowitz, 1991). Universities will have to reconsider the nature of these relations because developments in nanoscience and nanotechnology are likely to increase these effects. We can expect the continuous renegotiation of alliances among university, industry, and government (Senker, 1994).

Institutional and national boundaries are transcended in the course of creating new innovation environments. The public, private, and academic sectors, which formerly operated at arms length, are increasingly working together, with a spiral pattern of linkages emerging at different stages of the innovation process. What is called the “knowledge economy” has created a climate in which the ability to assemble and exploit knowledge has become a key competitive factor (Vanderburg, 2000). Understanding the roles and relations between academia, government, and industry could be the basis for assessing—and anticipating—the likely trajectories of technology-induced social change and help answer the following question: What model or models of innovation best explain the changes being ushered in by the revolution in nanotechnology?

### Conclusion

The process of innovation and the diffusion of benefits into society are only partially understood. Because nanotechnologies are likely to be diverse and their effects manifold, it is likely that several decades are required for their effects to be felt fully. Consequently, nanotechnology will coexist with established technologies rather than suddenly replace them. Because few social scientists have begun to examine the possible impacts of nanotechnology on society, their insights are often based on experience with earlier technologies (e.g., nuclear energy, information technology, biotechnology). It is important to explore some of the potential consequences arising from nanotechnology because differential rates of diffusion may create a “nano divide.” Like the digital divide following the introduction of new information and communication technologies, nanotechnology may facilitate tremendous inequalities between “nano haves” and “nano have nots.” Social and technological systems do not develop independently. The two evolve together in complex feedback loops, wherein each drives, restrains, and accelerates changes in the other. Understanding how developments in nanoscience and applications with nanotechnology are likely to diffuse is a critical part of anticipating these kinds of social and economic transformations (National Science Foundation, 2001).

### Note

1. For example, in 2001 the Canadian government, through the National Research Council, gave the University of Alberta \$120

million to create the National Institute for Nanotechnology (see [http://www.nrc.ca/nanotech/home\\_e.html](http://www.nrc.ca/nanotech/home_e.html)).

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