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An introduction to nanotechnology policy: Opportunities and constraints for emerging and established economies

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Abstract

Nanotechnology has captured wide attention all over the world and excited the imagination of young and old alike. Interest in the subject has increased remarkably during the last few years because of potential technological applications, and commercial interest has skyrocketed. The promise of nanotechnology as an economic engine that can redefine the wellbeing of regions and nations is pervasive; yet the imprecise language, and overuse of the term *nanotechnology*, has made that term fuzzier, broader, and trendier than many imagined possible. This is especially evident in nanotechnology market projections, which rose dramatically over the past five years as more traditional "product families" were engulfed by the expanding use of the term. Government policy regarding nanotechnology has often resembled an embrace of imagination rather than a systematic use of what Sun Tzu and others have taught about strategic decision making. Further, if nanotechnology is truly the next wave of technology product paradigms, how will we provide an educated workforce to support it? Moreover, in company with these societal benefits come increased societal risks. This paper is intended to provide policy makers and strategists with observations that might limit actions such as those that led to the "over-hype" of nanotechnology and to the fear (or discounting) of societal

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risks. In the latter case we might learn from the experiences of policy makers connected with other emerging enabling-technology bases, such as nuclear energy and, to a lesser extent, the "dot-com" boom.

1. Introduction

Nanotechnology has captured the public imagination [1]. Yet government policy for nanotechnology has more often resembled an embrace of imagination than a systematic use of what Sun Tzu [2] and others have taught us all about strategic decision making. Strategic decision making from most of these theorists includes the systematic inclusion of at least three items; the value of your effort, your competitors effort and the environment in which the decision or effort is taking place. The societal benefits of nanotechnology have been extolled without the caution that comes with a reasoned review of the societal risks that it may incur [3].

The current embrace of nanotechnology as the potential next "big commercial opportunity" [4] is built on a history of technology much older than is widely believed [5]. Nanotechnology-based products have been in commercial use for centuries. Perhaps the first product based on "bottom-up" nanoproperties of a material was carbon black. Does this fact diminish or enhance this technology base as part of "the next commercial wave of technologies," and if so why do we see these technologies as "emergent"? This is just one of the many questions that policy makers around the world have yet to answer [6].

One of the core problems that policy makers face is the ambiguity of the term *nanotechnology*. In recent years the prefix *nano* has come to be associated with almost anything new, small, molecular, atomic, trendy, ominous, or eye-catching. Major movies such as *The Stepford Wives*, *Spider-Man*, and *X-Men*, and books such as *Prey*, have linked the technology to "hyper hype" in order to sell entertainment. In a more serious vein, fascination with the term *nano* has elicited instances of unquestioning support by investors and cases of unreasoned fear by the general public; neither benefits the technology [7].

Any new technology will, and should, attract critical review. This is especially important for nanotechnology, due to its potential for far-reaching impact. Stakeholders are beginning to understand the attractive features that nanotechnology offers, yet participants in the nano-explosion, and the population as a whole, poorly understand the less desirable characteristics of nanotechnology. These aspects include the possible creative destruction of existing industry leading firms, new health concerns and secondary effects that we do not know. Numerous World Wide Web sites offer material that alternatively revels in or reviles nanotechnology's social impact. As always with pioneering science, the pace of social understanding lags technological progress.

A new fermentation of thought is forcing people to become aware or learn about nanotechnology. Learning connotes change, and in the main people do not embrace change; but greater understanding of nanotechnology must emerge nevertheless. First, an open and frank discussion on all aspects of the subject, including law [8], must continue. Second, and more importantly, there must be accessible and easily understood material for the purpose of nanotechnology education [9].

As the field develops, nanopolicy professionals will be expected to understand the nature of nanotechnology [1] and to have the opportunity–recognition skills of an entrepreneur [10,11]. They must also be able to weigh the positive and negative impacts of a potentially "creative destroying" technology [12] that has the promise of underpinning a Schumpeterian wave [13], and produce policy that will support the development of dynamic capitalism — underpinning an economic core that provides a firm foundation for ambitious firms that wish to increase their rates of growth [14]. Furthermore, if the nanotechnology revolution is a success, they will have been asked to provide programs that can support this revolution, regardless of the state of development of the economy they represent — a daunting task indeed.

In the following paragraphs we will provide samples of thought from renowned technology-based economic development thinkers from emerging and developed economies. This paper seeks to assist the policy maker and strategist in several ways. First we will provide a useful definition of nanotechnology, then we will explain the differentiation between nanotechnology and nanoscience [15]. Moreover, we will provide suggestions on nanotechnology commercialization, and examples of educational approaches, that may help policy makers and strategists to initiate reasoned policy. We will conclude with thoughts on the direction of nanotechnology policy [16].

2. Discussion

2.1. Useful categorizations

The many definitions of nanotechnology, some derived by government bodies [17,18], have migrated and expanded with the passage of time. Although research in this field dates back to Richard P. Feynman's classic presentation "Plenty of Room at the Bottom" [4], the term as technically defined is usually attributed to N. Taniguchi [19], while the commercial definition is attributed to K. Eric Drexler [20] as expressed in his work *Engines of Creation*. Initially the field was defined in a purely technological sense, but now definitions are being extended to include the concerns and interests of society as a whole, as expressed through the technological, commercial, populist, and ethicist communities. All good definitions provide some form of proactive engineering to the term *nanotechnology [Steve, will your audience understand what you mean by this?]*. For the nanopolicy or nano-strategy professional, perhaps a definition should comprise what nanotechnology is and what it is not. We provide one here that is derived from many that suggest that a certain technology can be considered a nanotechnology only if it involves all of the following three attributes:

1. Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1–100 nm range.
2. Creation and use of structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.
3. An ability to control or manipulate on the atomic or the nanoscale [18].

A further distinction between nanotechnology and nanoscience is important for nanopolicy makers since most would suggest that government policy promoting these endeavors are inherently different and require different kinds of resources and support. The Royal Academy of Science provides a valuable bifurcation of nanoscience and nanotechnology. To paraphrase, the Society suggests that:

Nanoscience is concerned with the study of phenomena and properties of materials that occur at extremely small length scales — "on the scale of atoms and molecules"; whereas nanotechnology "is the application of nanoscale science, engineering and technology to produce novel materials and devices such as materials for biological and medical applications" [21].

Other categorization techniques are important to a nanopolicy maker. These include: top-down versus bottom-up nanotechnology; bulk versus individually-addressed nanotechnology; and, most importantly for strategic choice, nanotechnology that is revolutionary in nature versus nanotechnology that is evolutionary in nature. We will briefly describe the first two, then focus on the last-named distinction [22].

Bottom-up nanotechnology is the growth of nanostructures one atom at a time. Top-down nanotechnology utilizes lithographic techniques such as semiconductor or MEMS lithography to print nanostructures, and is extensively used in what has become known as nanoelectronics. A further distinction is often made between bulk nanotechnology versus individually-addressed nanotechnology [23].

Bulk nanotechnology is the production of inorganic or organic materials in such a manner as to obtain nanotechnology based attributes in certain materials. This manufacturing methodology requires the availability of nanometer-size materials for inclusion in products. These nanoproducts are used to make existing materials better, and/or faster and/or cheaper. The steel industry and various chemical-based industries have been using bulk nanotechnology reactions to assist in the manufacture and improvement of their products for centuries.

Individually-addressed nanotechnology is the atom-by-atom or molecule-by-molecule manufacture of organic or inorganic material. It is often associated with self-assembly of materials, biologicals, or chemical-based systems. These manufacturing technologies are newer than most bulk applications.

The above categorization schemes are technological in nature and therefore important but not critical to the policy and strategy process. The evolutionary-versus-revolutionary nature of a nanotechnology is central to the nanopolicy-making process. Nanotechnology's potential for strategic impact is directly proportional to the magnitude of the impact that it can provide to a firm in revolutionizing the way a current product is made. However, a policy maker also must provide for an educational program that will ensure nanotechnology has a continuing source of educated workers.

Many nanotechnologies are revolutionary in nature and potentially disruptive. A technology is said to be disruptive if it can redefine the way to manufacture an existing product, and in doing so create a new or superior technology product paradigm. Thus, a disruptive technology renders the basic skills associated with the old technology useless and makes its infrastructure obsolete. When successful, a disruptive technology becomes the sustaining technology for a renewed industry. It could provide emerging markets with the opportunity to leapfrog legacy infrastructure, developed countries to redefine the basic competitive playing field, and the corporate have-nots a new opportunity for success [24].

Conversely, a technology is said to be evolutionary or sustaining when it supports the current technology-product paradigm. An example of evolutionary nanotechnology development is the creation of superior crystal development (grain-size) in metals. The development of fine structures at the nanometer scale in sophisticated cold-rolling (of specially alloyed steels), the development of nanocrystalline aluminum, and nanocrystalline powder technologies in ceramics, are examples of nanotechnologies acting in an evolutionary or sustaining role. Another example is the vast majority of established firms furthering their technology with nanoelectronics in an evolutionary manner. This type of nanotechnology further entrenches existing market leaders and regions of the world that dominate a given industrial segment [25].

If policy makers and strategists can define the nanotechnology competencies available in their region or companies, they can make policies and execute strategies that can enable them, or conversely they may not support them. Since semiconductor-based nanoelectronics will generally entrench current market leaders, it is unclear whether a new region would gain much from a deep investment in this arena, no matter how good the state of their competency in nanotechnology *per se*.

Nanotechnologies hold great promise as a font of new competencies. They are technologies converging at the interface, making some of the old "silo" thoughts on technology obsolete. They are pan-industrial, capable of providing foundations for many industries [4].

Innovations using nanotechnology are relevant to not only to developed countries but also to developing countries [26]. Nanotechnologies can provide solutions to some of the pressing problems these emerging economies face, especially in the rural sector. Some of the crucial problems facing these economies are infrastructural:

1. Energy production and storage
2. Providing potable drinking water
3. Improving agricultural production
4. Storage of agricultural products
5. Medical and health sector needs

Developing economies like India value the promise of nanotechnology for infrastructural development in particular. In the area of energy storage, improved efficiency of solar cells using nanotechnology has been a prime area of research in many large emerging economies [27]. Nanomaterials can be useful in designing better supercapacitors for the plaguing problem of energy storage. Hydrogen is a potential source of clean energy that can be stored efficiently in nanostructures. Nano-filter systems can filter bacteria, virus and other impurities from water, making it safe for drinking. Silver nanoparticles are of use in medical applications. Soil fertility and crop augmentation can be achieved with nanoparticles. Particles of variable pore sizes can be used for efficient slow release of fertilizers. Nanocapsules can be used to release their contents in a controlled manner, again increasing efficiency [28].

In the Indian context, a Nanoscience and Technology Initiative was formed by the Department of Science and Technology in 2001 [29]. Several laboratories established facilities to carry out research in nanoscience and technology. One of the major concerns in this new field is the development of the necessary manpower. The number of training centers is grossly inadequate, and greater commitment from the government is needed.

There is also need for a greater investment in nanoscience and technology. In this respect, China's investment in both people and infrastructure is higher than many of the developed countries. Several bilateral programs, mainly with the U.S., have been established.

Like India and China many developing countries are attempting to move ahead in nanotechnology, but this is increasingly difficult because of competition and the requirement for a high degree of technical sophistication.

The application of nanotechnology in areas related to health, particulate technology, and sensors, is already commercially viable, and more advances will be made in the near future. Nanodisplay devices are also likely to become commercial in the very near future. These solutions can be readily adapted by manufacturers in developing countries to solve national problems which also enjoy global markets. What is somewhat unsure is the area of nanoelectronics. While one may make a nano-transistor in the laboratory, the technology of integrating such devices is far away and is a focus of many developed countries. One can only hope that in the next 10–15 years a revolutionary form of nanoelectronics will become practicable as well.

Whatever the future, we must ensure that the benefits of nanotechnology research reach all of mankind.

If nanotechnology can form the basis of an economic and social boon and if it is truly different in many ways from traditional technologies, then what is the appropriate manner for providing education for its support? Nanotechnology is a convergence of many technologies working at the interface, requiring that differing skills be taught throughout the entire educational process from grade school and high school science, engineering, social studies and history through Ph.D. programs in engineering, science, management and the humanities. Though much of a region's or a nation's initial tangible fiscal expression of its technology policy is often provided in "nanocenters of excellence," some far-sighted countries are also trying to teach the skills to existing workforces. Though such initiatives are necessary to embrace the nanotechnology revolution, many countries are slow to recognize the challenges and the opportunities. Further, some governmental laboratories have mandates to embrace the educational challenge inherent in nanotechnology development, and are initiating those efforts. Concurrently, one wonders how many corporations and industries are providing fiscal incentives to help determine what they should be doing in educating their workforces (for example, by employing the science of muddling through, or learning by doing [30]) before acting, to help ensure that such education will be high quality, and that it will acquire its much-needed status and support.

Finally, the scientific field of nanotechnology is developing extremely rapidly, many application areas outpacing society's ability to provide a policy structure that weighs the benefits and risks that it might provide. A. Romig [4] has stated that: "We must strive to use nanotechnology to improve human life through better healthcare, cleaner environments and improved national security, we must work to detect and assess the negative impacts that nanotechnology (or any technology) might bring. This is further emphasized by a review of the United State National Nanotechnology Initiative (NNI) pointing out the need to increase efforts to ensure that "the societal implications of Nanoscale science and Technology become and integrated and vital component of its operation [31]."

3. Conclusions

Emerging as well as established economies are embracing nanotechnologies not only because of its promise to address pressing infrastructural needs, but also because of its ability to leave a competency legacy that might well form the basis of the next Kondratieff [32] or Schumpeterian [13] economic long wave. Nanotechnology is an emerging, enabling, and often disruptive technology base that is pan-industrial as well as convergent. It defies the idea of a single technology or industrial category, to emerge as the sinew that binds many new converging technologies. It has the potential to provide large emerging economies the chance to leapfrog established technology platforms by creating their own nanotechnology-based solutions and parley this into the formation of new industries. Similarly, established economies see nanotechnology as an emerging economic wave, attempting to obtain competitive advantage from these new paradigms by focusing on past competencies that they can enhance with nanotechnology.

These benefits must be tempered by policies that acknowledge that new risks may arise from the exploitation of nanotechnology. We must understand that we are creatively destroying old methods of manufacture and undertaking national efforts to create a new workforce to meet new industrial needs. These changes are transformational, and they are revolutionary. Many recognize that if successful, these new technology regimes will have an effect on the relative strength of national and regional economies similar to that experienced in the first Industrial Revolution. Many nations wish to introduce the harbingers of new industries that are created as technologies converge under the influence of nanotechnology. Fortunately, many have learned from past encounters with emergent enabling technologies and related efforts to ensure that learning and development of proper policies that leverage the value of nanotechnology are now underway.

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