THE FUTURE OF NANOTECHNOLOGIES

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Abstract

Nanotechnology is the first major worldwide research initiative of the 21st century. Nanotechnologies are applied to cross industrial problems and are a general purpose technology that acts as both a basis for technology solutions or at the convergence of other enabling technologies, like biotechnologies, computational sciences, physical sciences, communication technologies, cognitive sciences, social psychology and other social sciences. Nanotechnologies are pervasive solution vectors in our economic environment. It is necessary to develop new methods to assess nanotechnologies development to better understand nanotechnology based innovation. As general purpose and enabling technologies, nanotechnologies reveal commercialization processes, from start-ups to large firms in collaboration with public sector research, and which lead to changing patterns of industrial organization which influence public policy initiatives to foster their development.

Keywords: Nanotechnology; general purpose technology; pan-industrial; convergence; hybridization; commercialization

The aim of this introductory paper is to present a state-of-the-art synthesis of current thinking about the management of nanotechnologies. As general purpose and enabling technologies, nanotechnologies promise to make far-reaching changes in how technologies are evaluated, how they relate to industrial organization and how such on-going transformations should be understood. Anticipating the future, it seems that nanotechnologies' generalized diffusion will turn them into commodities, creating more space for dedicated, higher added value applications such as nanobiotechnologies, nanoenergy or nanomaterials.

Nanotechnology is the first major worldwide research initiative of the 21st century. Nanotechnologies are general purpose technologies that act as both the basis for technology solutions across a range of industrial problems or as a nexus for the convergence of other enabling technologies like biotechnologies, computational sciences, physical sciences, communication technologies, cognitive sciences, social psychology and other social sciences (Freitas Jr, 2010; Hyungsub *et al.*, 2009; Kautt *et al.*, 2007; Linton *et al.*, 2004). As for sustainability (Linton *et al.*, 2007), the cross-industry and convergent nature of nanotechnology-based solutions promises to transform nearly every aspect of life (Compano *et al.*, 2006, Tierney, 2011 #10816; Loveridge *et al.*, 2008; Malanowski *et al.*, 2007) – for instance, via having opened the door to engineering at the molecular level (Drexler, 1986a; Walsh, 2004). Some see nanotechnologies as a field on their own, while others see their value in enabling a general trend of miniaturization in all physical technologies: either way, it is widely assumed that they will be pervasive solution vectors in our future economic environment. Applications employing nanotechnologies promise greater and more equal access to knowledge and information; new therapeutic interventions; improved environmental monitoring; greater safety and security; expanded communication capacities and many other industrial and societal applications. The enabling cross-industrial technology base (Fynman, 1960) they provide is being increasingly incorporated into existing products or processes to optimize production processes and produce better products with enhanced characteristics. In commercial terms, customers and users are only aware of nanotechnology-enabled products via their greatly increased functionality - in physically terms, individual nanotechnologies are invisible to the human eye. Their physical characteristics vary greatly from those of their macro counterparts, significantly affecting their internal design, their manufacture and their functionalities. The commercial promise of nanotechnology - as both the general foundation for and specific enabler of new innovations - makes it likely to underpin the next Schumpeterian wave of economic development (Wonglimpiyara, 2005) and its commercial promises has been formulated around its potential for facilitating such transformations (Selin, 2007).

From breakthrough discoveries to general purpose technologies

This technology base was first discussed in the last half of the 20th century - technically by (Fynman, 1960) and commercially by Drexler (Drexler, 1986b) and took decades to generate significant public investment. Huge public investments to support scientific and technological researches (Shapira *et al.*, 2011; Teece, 2011), the creation of technological and industrial platforms and infrastructures (mainly in the 21st century) have led to more than 2,000,000 articles related to nanotechnologies being published, and over 1,000,000 applications lodged with patent offices (Mangematin *et al.*, 2012; Youtie *et al.*, 2008b). Yet a significant question remains: To what extent does recent empirical evidence match the technologies' initial promises? Are nanotechnologies the next 'Schumpeterian Wave' which will revolutionize many industry sectors? Will they bring radical change to many scientific and technological fields, converging previously distinct technology-driven sectors in ways that will benefit economies and consumers alike (Allarakhia *et al.*, 2011; Linton *et al.*, 2008)? Or is it all just hype designed to mobilize energy and to renew investments in existing fields (Grodal, 2010)?

Current nanotechnology developments have been successful up to a point: products incorporating nanotechnology based devices are on the markets, start-ups have been created and large firms have invested in production capacities (Fiedler *et al.*, 2010, , 2011; Groen *et al.*, 2008; Huang *et al.*, 2011; Newbert *et al.*, 2007; Palmberg, 2008). Nanoscience and Nanotechnology research is rapidly advancing, the rate of growth of the scientific production remains up to 10% per year, and nanotechnology based product innovations are increasing; Nanotechnologies are general purpose technologies (Gambardella *et al.*, 2010). This is the reason why they are the objects of significant investments by incumbents (Rothaermel *et al.*, 2007). So nanotechnologies are emerging, although the processes involved different from those that characterized the birth of the biotechnologies. Their pan-industry nature is illustrated not just through the adoption of nano-product paradigms - such as materials, devices, systems and components - but also by their ability to change industries radically - or even to create such new sectors as nanobiotechnologies (Allarakhia *et al.*, 2011; Kuzma *et al.*, 2010), nano-energy (Ying *et al.*, 2010), nano-materials, nano- chemistry or nanoelectronics (Lee *et al.*, 2007). Some sort of convergence is showing, with the emergence of nano-engines, new diagnostic tools hybridizing nanoelectronics and biotechnologies.

Nanotechnology has been seen as critical to 21st century scientific advancement, technology development, product innovation, and social innovation. The century's problems have been seen as convergent, and their solutions as likely to require emerging technologies that create new product paradigms at the interfaces with other technologies (Nikulainen *et al.*). Some futurists consider nanotechnologies to be the foundation of the world's next economy, but our commercial and social understanding of the implications of the phenomena lags behind our scientific appreciation of its possibilities (Islam *et al.*, 2010). This special issue advances our knowledge both about the foundations and the likely effects of nanotechnology.

Understanding the future of nanotechnologies

Nine scholarly works contribute to our understanding of nanotechnology based innovation.

New methodologies

The first two papers propose new methodologies for evaluating nanotechnologies: An Chin Cheng (Chin cheng, 2012) has improved the field by developing a valuation methodology for the selection of new materials technology. He utilizes the 'fuzzy AHP' method to obtain the opinions of professionals and showed that, amongst seven evaluation criteria, 'data validity' has the highest weighting, followed by 'method adaptability' and 'technology development evaluability'. He concludes that the 'real options' approach and income methods are the two most applicable methods for evaluating new materials development. Wang Chunhsien (Chunhsien, 2012) discusses and evaluates the commercialization performance of nanoproducts from consumer perspectives. He constructs a series of nanoproducts' importance attributes and performance evaluation maps to identify areas for improvement. These evaluation methods are not dedicated to nanotechnologies – even if they were developed for nanotechnologies they promise to be useful for other technology inquires as well.

Value creation

Our special issue furthers our understanding of nanotechnology commercialization with two studies. The first, based on 12 case studies of new ventures, Maine et al. (Maine, 2012) examine how firms create value from nanotechnologies, and show that firms exploiting nanotechnology based process innovation face greater uncertainty in their value chain positioning, market breadth, customization, and require more changes of their customers compared to more often studied product-based ventures (Cohendet *et al.*, 2009; Packalen, 2007). They also show that nanotechnology ventures benefit from prioritizing technology-market matching, alliance building and experimenting with technologies in new value networks. The second study in this section – by Juanola-Feliu et al. (Juanola-Feliu, 2012) – develops our understanding of nanotechnology based diagnostics through an in depth review of a cutting-edge biomedical device for continuous in-vivo glucose monitoring, which is made possible by the convergence of medicine, physics, chemistry, biology, telecommunications, and electronics and energy researches. The paper traces how the process of commercializing the device required the alignment of a variety of different stakeholders – University, Hospital, Industry, Administration and society. Both of these works progress the knowledge of nanotechnology commercialization by revealing different commercialization processes, from start-ups to large firms in collaboration with public sector research.

Changing patterns of industrial organization

Three papers analyze the changing patterns of industrial organizations in nanotechnologies (Jiang *et al.*, 2011; Munari *et al.*, 2011). First, Genet et al. (Genet, 2012) examine the patterns of technology transfer in nanotechnology. They compare the biotech technology transfer model - where start-ups and small firms bridged the collaborations between large firms and universities – with the technology transfer processes used in microelectronics to illustrate the differences between them and the nanotechnology transfer model. For example, while SMEs played valuable technology-bridging roles in the emergence of the biotechnologies and the central function of 'translating' new knowledge between public research and industry in technologies is carried by the larger firms, as it was in microelectronics, with SMEs playing the role of specialized providers. These results echo those recently published on US data (Thursby *et al.*, 2011), and suggest that patterns of collaborations are context specific (Fiedler *et al.*, 2010). Allarakhia and Walsh (Allarakhia *et* *al.*, 2012) propose a method to manage, select, analyze and design large consortia which are central to commercial progress in nano-technology fields. They present a diagnostic tool to assess consortia centered on the technologies' commercial promise, adapting Institutional Analysis Development (IAD) to integrate nanotechnology innovators as well as their stakeholders (governments, industries, large firms, SME, entrepreneurial enterprises and supporting firms). von Raesfeld *et al.* (von Raesfeld, 2012) examine the determinants of the potential collaboration project performances in the Netherlands, by assessing the commercial performance of 169 nanotechnology research projects five years after their completion. She shows the strong positive impact of participants' skills complementarity, commitment and technological experience on both the projects' invention and financial performance, suggesting that project-based organization favors the hybridization of complementary competencies (Avenel *et al.*, 2007; Bonaccorsi *et al.*, 2007).

Finally, we have two papers which further the discussion of public policy initiatives to foster nanotechnology developments. Battard (Battard, 2012) discusses the formation of nanocenters and argues that research groups dedicated to nanotechnology are technological hubs where scientists with multiple backgrounds converge in order to conduct research at the nanoscale. These hubs inherit from established scientific disciplines, but create local practices and knowledge, and their multidisciplinary context and the absence of standards can create misalignment for junior scientists between their initial discipline, their research and the outcomes they are expected to produce. Battard's analysis questions the emergence of nanotechnology as a discipline, as most scientists remain closely linked to their original disciplines. Battard's observation at the micro-level is confirmed by Baglieri et al. (Baglieri *et al.*, 2012). Nanotechnologies are developed by a small number of large clusters worldwide (Grimpe *et al.*, 2011; Mangematin *et al.*, 2012; Meyer *et al.*, 2011; Robinson *et al.*, 2007; Youtie *et al.*, 2008b). Comparing two nano-electronics clusters - Grenoble (France) and

Catania (Italy) - the authors emphasize the role of scientific and technological diversity, competition for cluster orchestration and overlap between networks in stimulating cluster evolution. They point out that competition to orchestrate clusters stimulates 'sleeping anchor' tenants to influence cluster research avenues, and shape new networks within and beyond its boundaries. Cluster evolution is based on hybridization with existing technological fields that using nanotechnologies, such as nano-energy or nano biotechnology. (Kajikawa *et al.*, 2010).

The paradox of nanotechnologies

Since Drexler (1986) who introduce the term nanotechnologies and the development of the first critical nanotechnology roadmaps (Bozeman *et al.*, 2007; Walsh, 2004), the deployment of nanotechnologies has become clearer. Incumbents play the central roles (Allarakhia *et al.*, 2011; Jiang *et al.*, 2011; Mangematin *et al.*, 2011), with start-ups and SMEs acting as specialized suppliers while large firms and public sector research organizations form direct alliances to develop and to market nanotechnologies. Nanotechnology-based devices are incorporated in existing products and embedded in production processes. Convergence or hybridization is very progressive, leading to the design of new products that merge two or three different bodies of technologies. Scientific convergence appears to be slower than the integration of nanotechnologies in existing or new products or processes. New centers have been created to host the different scientists working at the nanoscale level (Kautt *et al.*, 2007), and new scientific communities have emerged building on existing disciplines but using new techniques and facing new problems. These activities confirm the sense of nanotechnologies as general purpose technologies which impact a wide range of scientific and technological fields and change how research and production processes are performed. As Arora and Gambardella (Arora, 1994) have pointed out in biotechnology, nanotechnologies are changing the *“technology of technological change”*, but affecting different scientific fields and different industries.

Paraphrasing Solow’s paradox about computers, we can say that nanotechnologies are found everywhere except as a new industry or a new scientific field. Anderson (Andersen, 2011) emphasizes silent innovation; Battard describes new nanotechnology centers as technological hubs; Genet *et al.* underline how nanotechnology technology transfer mechanisms resemble those in microelectronics. Industrial organization appears not to be specific either (Jiang *et al.*, 2011; Mangematin *et al.*, 2011; Youtie *et al.*, 2008a) - start-ups and small firms are created as specialized suppliers since (as Maine et al. (Maine, 2012) as point out) the market is large enough to accommodate niche sectors, while alliances and collaborations appear to reproduce their patterns in microelectronics and biotechnologies, involving different actors in creating, manufacturing and commercializing complex products and services.

This special issue has two blind spots. First, questions of regulation and societal acceptance of nanotechnologies remain important issues to explore. The Technovation special issue on “the future of nanotechnologies” does not address the evolution of institutions and the interplay between acceptance, strategies and the formation of markets (Allan *et al.*, 2010; Throne-Holst *et al.*, 2008; Yawson *et al.*, 2010). Second, nanotechnologies are not only general purpose technologies – they are also technologies that enable the creation of new devices and new ways to improve the quality of life. Nanotechnologies are embedded in existing industries and research using nanotechnologies are developed within existing fields, transforming them from microelectronics to nano-electronics, from biotechnologies to nano-biotechnologies, and from energy to nano energy. Firms are exploring new ways to address consumer needs, new business models based on the changes nanotechnologies could enable in existing industries. The multiplication of competing business models may transform industry logics, as it has been the case for the music industry or for digital photography (Bettis *et al.*, 1995; Munir, 2005; Sabatier *et al.*, 2011). What sort of transformations can we expect? What dominant logics will be challenged and in which industries? Such questions open room for new research.

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