

# *What Drives Innovation? Causes of and Consequences for Nanotechnologies*

Ingrid Ott  
Christian Papilloud  
Torben Zülsdorf

Nanotechnologies are expected to be the dominant general purpose technology of the next decades. Their market potential is immense and not only supply-side but especially demand-side arguments will have far reaching consequences for innovations. The latter may occur as increased miniaturization or via building completely new products, processes or services. Innovations in the field of nanotechnologies do not only affect productivity in downstream sectors but these feed back to nanotechnologies thereby inducing circles of continuing innovation. Demand for nano-components mainly arises from firms while private demand is assigned to final products, processes or services that are augmented by nanotechnologies. Due to the technology's controversial character, the consumer's attitude towards risk and technology affects private demand and this may either spur or hamper innovation. The paper aims to unravel how these complex interdependencies and feedback mechanisms affect overall innovation in downstream sectors that is induced by nanotechnologies and how this for its part affects further improvements of nanotechnologies.

*Key Words:* general purpose technologies, controversial technologies, determinants of innovation

*JEL Classification:* O33, Z13

## **Introduction**

Future decades are expected to be largely dominated by increased utilization and spread of nanotechnologies. This term broadly refers to tech-

*Ingrid Ott is Head of the group 'Innovation and Growth' at the Hamburg Institute of International Economics, Germany, and Research Associate at the Kiel Institute for the World Economy, Germany.*

*Christian Papilloud is professor at the UFR des Sciences de l'Homme, Université de Caen Basse-Normandie, France and invited professor at the Leuphana University of Lüneburg, Germany.*

*Torben Zülsdorf is junior researcher at the Hamburg Institute of International Economics, Germany.*

*Managing Global Transitions* 7 (1): 5–26

nologies and devices whose unifying theme is the control of matter at an atomic and molecular scale, namely with critical dimensions smaller than 100 nanometers. The manipulation of nanostructures leads to the observation of completely new phenomena and with this prepares the ground for considerable innovations. The goal of this paper is to give an overview on some most important lines of argumentations relevant in the context of the complex innovation process of nanotechnologies. In doing so the paper provides a theoretical framework for discussing the potential but also possible frictions of that newly emerging technology.

Permanent innovation is especially important for those countries that are poorly endowed with natural resources in order to be competitive at an international level and to realize ongoing growth (see e. g. Barro and Sala-i-Martin 2004; Acemoglu 2009 for a recent overview on the link between innovation and growth). A more precise look at innovation determinants reveals that it is possible for most eras to identify a certain technology that has a key function for the generation of innovations in other fields (see e. g. Rosenberg 1992). This has led to the distinction in drastic and incremental innovations. Drastic innovations frequently spur incremental innovations in complementary fields thereby introducing far-reaching economic and societal effects. If drastic innovations have the potential for pervasive utilization – as e. g. the steam engine, electricity or the computer – they are called *general purpose technologies* (see e. g. Bresnahan and Trajtenberg 1995 who coined that term).

Although they may basically be used in a variety of applications this neither implies any automatism concerning diffusion nor that efficiency considerations are the only determinant driving demand for the new technology. This argument becomes strikingly obvious in the context of so-called *controversial technologies* – a notion stating that it is not per se clear whether, from an aggregate point of view, chances or possible risks of the innovation dominate (biotechnology or nuclear power are some prominent examples of such a kind of technology). Given this, individual attitudes towards technologies and risk become important for the development and diffusion of the innovation. In the extreme, failing public acceptance may interrupt the innovation process.

One might conclude that usually innovation processes are driven by demand-side as well as by supply-side arguments, in which each position holds a certain role. Throughout this paper *supply-side arguments* will be discussed in the context of general purpose technologies, thereby including a microeconomic and a macroeconomic perspective. From the point of view of single firms, the most important are externalities and feedback

effects that arise along the value chain. As a consequence too few innovations are realized, and on top of that they arise too late. The aggregate perspective adds further arguments, namely the impact of general purpose technologies on total factor productivity. Following the logic of the so-called productivity paradox, the implementation of a new general purpose technology only enhances overall productivity in the long-run whereas, due to costly adjustment processes, in the short-run even productivity losses may arise. A second perspective focuses on *demand-side arguments* mainly arising in the context of controversial technologies. These approaches do not focus on pure technological aspects but lay emphasis on the needs, preferences and the utility of the users.

Several features qualify nanotechnologies as the future dominating *general purpose technology*. One is pervasiveness, since the technology may be utilized in lots of animate and inanimate fields. Due to their tiny size nanotechnologies are used at the origins of the value creation chain and induce high technological dynamics. Improvements in nanotechnologies also affect productivity in the downstream sectors, which due to technological dynamics, again spurs innovation in the upstream technology. As a consequence, not only production but also innovation processes are vertically linked, at which the latter interdependency runs in both directions along the value creation chain. But aside from this, nanotechnologies are also understood as representing a *controversial technology* and great efforts are made to avoid interruptions in the innovation process that might arise as a consequence of failing public acceptance.

The remainder of the paper is as follows: the second section presents determinants and economic aspects of general purpose technologies. The third section analyzes supply-side and demand-side arguments of innovation in the case of controversial technologies. The fourth section applies the arguments detailed before on the case of nanotechnologies. The fifth section briefly concludes.

## **Economic Aspects of General Purpose Technologies**

### DRASTIC VERSUS INCREMENTAL INNOVATIONS

In the simplest form, technological progress arises as an incremental process that improves the efficiency of resource deployment. It may not be uniform across sectors or time, but the aggregate effects are relatively smooth.<sup>1</sup> In contrast are major inventions that have had far-reaching and prolonged implications, such as the steam engine, electricity, or the computer. The distinction between drastic and incremental innovation is

useful, since frequently incremental innovations – although taking place in the regular course of business – follow drastic innovations. A drastic innovation, however, introduces a discontinuity in the organization of the economy in the sense that the innovation replaces an old technology that played a significant role in an industry with new methods of production. Or it replaces an old material that performed certain functions with a new one.<sup>2</sup>

Note that a discontinuity in this sense does not automatically imply a necessary discontinuity in the observed pattern of resource allocation or the evolution of output. The introduction of a superior technology can be gradual, starting with a negligible absorption of resources which is followed by continuous expansion over time.<sup>3</sup> It is nevertheless helpful to distinguish between drastic and incremental innovations since the latter frequently are triggered by drastic innovations. Put differently, drastic innovations induce series of incremental (and often complementary) innovations.

The distinction between drastic and incremental innovations is also helpful with respect to their emergence: It is possible that forces driving incremental innovations are different from those that drive drastic innovations. For example, incremental innovations are more susceptible to standard profitability calculations, even when they involve externalities and are subject to risk, simply because markets can evaluate their profitability. In contrast, drastic innovations face much larger uncertainties, producing risks that are much harder to evaluate by the market (see e. g. Rosenberg 1996). As a result, drastic innovators can engage little in risk-sharing and have to bear most of the risk themselves.<sup>4</sup>

#### PECULIARITIES OF GENERAL PURPOSE TECHNOLOGIES

A drastic innovation qualifies as general purpose technology if it has the potential for pervasive use in a wide range of sectors in ways that drastically change their modes of operation. To quote from Bresnahan and Trajtenberg (1995), who coined the term general purpose technology and provided a highly original discussion of its usefulness:<sup>5</sup>

Most GPTs play the role of ‘enabling technologies,’ opening up new opportunities rather than offering complete, final solutions. For example, the productivity gains associated with the introduction of electric motors in manufacturing were not limited to a reduction in energy costs. The new energy sources fostered the more efficient design of factories, taking advantage of the newfound flexibility of electric power. Similarly, the users

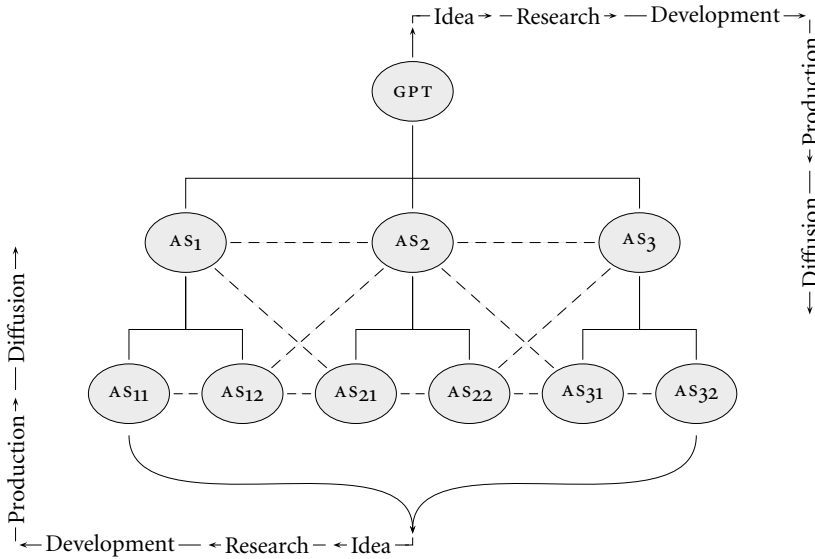


FIGURE 1 Generality of purpose and innovational complementarities (GPT – general purpose technology; AS – applying sector)

of microelectronics benefit from the surging power of silicon by wrapping around the integrated circuits their own technical advantages. This phenomenon involves what we call ‘innovational complementarities’ (IC), that is, the productivity of R&D in a downstream sector increases as a consequence of innovation in the GPT. These complementarities magnify the effects of innovation in the GPT, and help propagate them throughout the economy.

The description makes clear two most important features of drastic innovations that qualify as general purpose technologies: generality of purpose as well as innovational complementarities.<sup>6</sup> When these effects are particularly strong, as for example in the case of electricity, information and communication technologies and the internet or henceforth nanotechnologies, they lead to considerable changes in economic organizations. Sometimes they also affect the organization of society through changes in working hours, constraints of family life, social stratification, and the like.<sup>7</sup>

One immediate consequence of pervasiveness are strong interdependencies between lots of actors along the value creation chain. Figure 1 contains a technology tree that illustrates horizontal and vertical linkages, that arise between the general purpose technology (denoted by

GPT) and downstream sectors (applying sectors, hence AS) which apply the technology. The generality of purpose is indicated by the vertical linkages while horizontal lines between the applying sectors illustrate that also firms at the same level of the value creation chain are basically interrelated. Figure 1 also contains two innovation processes (from the pure idea until diffusion) which are indicated by the outside arrows. One innovation process begins at the level of the general purpose technology and works downwards along the value creation chain. Diffusion then takes place via utilization of the general purpose technology in downstream sectors in which the technology plays the role of an intermediate input, and diffusion along the technology tree takes place in the form of a cascade. Additionally, figure 1 encompasses a second innovation process which, in turn, comes from the applying sector and goes back to the general purpose technology and hence runs upwards along the value creation chain. This indicates that inherent to the general purpose technology there is the potential of technological improvement that runs in two directions.<sup>8</sup> The utilization of the general purpose technology by the downstream firms reveals potential for improvement and hence induces innovation processes in the upstream sector, namely the general purpose technology. This, in turn, induces improvements in the upstream general purpose technology which again feed back to downstream sectors and so forth.

As argued in the context of figure 1, numerous interactions exist between upstream and downstream sectors. These interdependencies do not only arise in a production context but also during the innovation processes within companies. They incorporate two fundamental externalities:<sup>9</sup>

- *Vertical externalities.* Due to innovational complementarities, the innovation activities in upstream and downstream industries are related, and firms in upstream and downstream sectors have linked payoffs. As long as each firm decides individually, it does not consider the aggregate effects arising from its individual action. Consequently, the well-known appropriability effect (namely the failing to appropriate the entire returns of individual activities) arises (see Helpman and Trajtenberg 1998). A familiar problem of imperfect access to the social returns arises, except that in the context of general purpose technologies it runs in both ways. This encompasses a bilateral moral hazard problem which implies that not any side, neither the upstream nor the downstream firm, will have sufficient

incentives to innovate. As a consequence, the innovation incentives along the entire value creation chain are too little with respect to the extent and arise too late.

- *Horizontal externalities.* Applying sectors include actual and possible users of the general purpose technology. Their demand depends positively upon the quality and negatively upon the price of the general purpose technology. At the same time, quality within the general purpose technology sector depends on marginal production costs and on the (aggregate) technological level of all applying sectors. Hence, if one single applying sector innovates to increase its own technological level (with the goal of reducing own production costs) also the aggregate level of all applying sectors will increase. This leads to improvements within the general purpose technology and hence to reduced costs not only in the originally innovating sector but also in the other (non-innovating) downstream sectors. However, as argued before, again the appropriability effect comes into action, and again this induces a moral hazard problem: Why should any applying sector innovate if it could benefit at zero costs from the innovation in another sector?

To sum up: As Bresnahan and Trajtenberg (1995) noted, general purpose technologies introduce two types of externalities: one between the general purpose technology and the application sectors (vertical); another across the application sectors (horizontal). The former stems from the difficulties that an inventor of the general purpose technology may have in appropriating the fruits of the invention. When institutional conditions prevent full appropriation, the general purpose technology is effectively underpriced and therefore undersupplied. The latter occurs since the application sectors are not coordinated and each one conditions its expansion of the available general purpose technology. If in contrast they coordinated a joint expansion, they would raise the profitability of the general purpose technology and encourage its improvement. A better general purpose technology fits them all. Consequently, coordination of a joint expansion – and with this the conditions of demand – are of major importance for the diffusion and thus improvement of the general purpose technology, which in the end benefits all.

#### GENERAL PURPOSE TECHNOLOGIES AND AGGREGATE GROWTH

From an economic point of view, general purpose technologies are not only interesting from a microeconomic perspective but they have also

some peculiarities with respect to their aggregate effect or, to be more precise, for aggregate growth. As has been widely shown by economic historians, in any given period, there exist some technologies that play a far-reaching role in the sense that they bring about sustained and pervasive productivity gains and which, in consequence, widely foster economic growth. Some examples are the steam engine during the industrial revolution, electricity during the first decades, or microelectronics in the second half of the 20th century. Nanotechnologies are expected to induce the next long-run wave.<sup>10</sup> The basic argumentation is as follows: As an improved version of the general purpose technology becomes available it gets adopted by an increasing number of application sectors which, in turn, are accompanied by further advances, thus raising the attractiveness of further adoption. This increases the demand for the general purpose technology, thereby inducing improvements of the general purpose technology, which then prompts a new round of advances in the application sectors, and so forth. As the effects become significant at an aggregate level, the general purpose technology finally affects overall growth. However, even if substantially important in the long-run, new technologies may at first have no significant impact on actual growth, since they have to await for the development of a sufficiently large amount of complementary assets in the applying sector. Moreover, these assets use up resources and hence, in the short run, growth may even be negatively affected.

This latter aspect of the so-called ‘productivity paradox’ has been formalized e. g. by Helpman and Trajtenberg (1998) who develop a growth model which allows for studying the economy-wide dynamics that the emergence of a new general purpose technology may generate. Within this paper we just present a short sketch of the model’s simplest version without going into formal details, thereby assuming that advances in the general purpose technology are exogenous. Hence we abstract from analyzing the implications of innovational complementarities illustrated before. To keep the discussion simple we focus on the role of complementarity in the sense that the downstream sectors, which provide components that are complementary to the general purpose technology, and their incentives for innovation are of primary interest.<sup>11</sup> Figure 2 provides a simple illustration of the relevant interdependencies.

Figure 2 contains a stylized sequence of the emergence of a new general purpose technology which contains three cycles. Each cycle is denoted by  $\Delta$  and describes a phase in which a certain general purpose technology,



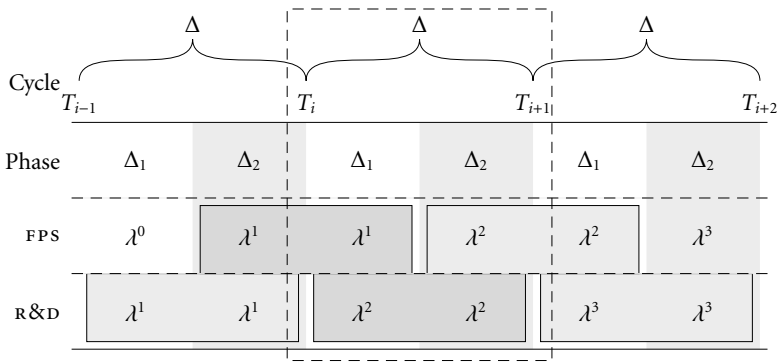


FIGURE 2 The importance of complements ( $T_1$  – availability of  $GPT_1$ , start of development of components for  $GPT_{i+1}$ ,  $T_i + \Delta_1$  – switch in the FPS to  $GPT_{i+1}$ ,  $\Delta$  – phase in which a general purpose technology is available;  $\Delta_1$  – phase with productivity decline;  $\Delta_2$  – phase with productivity growth;  $\lambda^i$  – general purpose technology at work; FPS – final product sector; R&D – research and development)

denoted by  $\lambda^i$ , is at work. The positive parameter  $i$  is ordinal and indicates the consecutive number of the current general purpose technology. The parameter  $\lambda$  is assumed to exceed unity, hence a newer GPT implies higher values of  $\lambda^i$ .

Since the general purpose technology is not a lonely standing technology but is applied to a variety of uses we distinguish the utilization within the final product sector (denoted by FPS) and in the component sector (denoted by R&D). Each cycle is divided into two phases,  $\Delta_1$  and  $\Delta_2$ ; both may be distinguished as follows: Within the first phase,  $\Delta_1$ , final output is manufactured with the old general purpose technology,  $\lambda^i$ , while innovators already develop components for the new general purpose technology,  $\lambda^{i+1}$ . Consequently, the number of components for  $\lambda^{i+1}$  rises over time. Note that the development of components for the next technology comes at the cost of negative output and productivity growth, stagnating real wages, and declining profit shares. In the second phase,  $\Delta_2$ , after a sufficient amount of components for the new general purpose technology has been developed, manufacturers of final output switch to the new technology,  $\lambda^{i+1}$ , while innovators still continue to develop components for this technology. Then the benefits of an advanced general purpose technology manifest themselves. As a consequence, output, real wages, and profits rise.

In figure 2 this becomes apparent while looking at the general purpose

technology at work within the separate sectors, namely the sectors for final goods production and the one for the development of components: While during  $\Delta_1$  two different general purpose technologies (e. g.  $\lambda^1$  and  $\lambda^2$ ) affect economic activity in the respective sector,  $\Delta_2$  is characterized by the overall utilization of the most recent general purpose technology (e. g.  $\lambda^2$ ) in both the component and the final product sector.

To sum up: Within each cycle, the analysis shows the centrality that complementary investments play in the aggregate growth process. Above it is shown how the sequential and cumulative nature of such complementary investments may induce different phases along each cycle, each of them exhibiting very different features. Of special interest is the initial phase of negative or below average growth. This results from the fact that there exists a threshold level of complementary inputs that needs to be developed before the general purpose technology at work in final goods' production can be displaced by the newest one. Hence one has to carefully consider the time line in assessing the growth impact of general purpose technologies: while aggregate growth increases in the long-run due to productivity gains of the improved GPT and the complementary components (second phase), productivity initially declines as a consequence of parallel use of two GPT during the first phase.

## **Innovation and International Competitiveness**

### SUPPLY AND DEMAND SIDE ARGUMENTS

Until here the argumentation referred to the interdependencies between upstream and downstream sectors, the arising coordination problem that ends up in too little and too late innovation, and delayed growth effects induced by the general purpose technology. This perspective already underlines the fundamental point of the development of general purpose technologies, namely the role of demand. As we argue along the technology tree, not only demand for final products but also firms' demands that arise along the value creation chain gains importance.

As argued before, those theories that focus on the *supply-side* frequently stress the implications of knowledge as (at least a partial) public good. Innovative firms are not able to appropriate all returns that are generated by their innovation activities while they have to cover the entire costs. Consequently the incentive for innovation is sub-optimally low and the innovation process is accompanied by market failures. This justifies governmental intervention in the innovation process frequently

in the form of direct or indirect subsidies.<sup>12</sup> In addition, supply of new products, processes or services is also affected by national tax systems, the availability of qualified labor or other input factors, as well as by co-operation possibilities with component suppliers or other firms.

In contrast to this a relevant impact for continuous innovation stems from ambitious customers, the market structure as well as from economies of scale and scope in production. Picking up this argument, other approaches emphasize the role of the *demand-side* for the generation of knowledge, innovation and international competitiveness (see e. g. Linder 1961; Blümle 1994; Fagerberg 1995). These approaches do not focus on pure technological aspects but lay an emphasis on the needs and the utility of the users. Summarizing these arguments, Beise and Cleff (2004) or Gerybadze, Meyer-Kramer, and Reger (1997) focus on so called *lead markets* that enable promising technologies to emerge. Lead markets arise if there exists a critical amount of users, whose needs determine the quality of demand. *Lead users* (in contrast to ‘normal users’) may be characterized as follows: (i) they are precursors of a broad commercial market and hence early anticipators of global trends, (ii) they expect high utility from new products, processes or services, (iii) they claim for the implantation of ideas and inventions in final products, processes and services, and (iv) fall back on local resources. Aside from private individuals or firms, also governments may become lead users, e. g. by buying special products or services or by issuing research orders for them. Typically, the government is especially important in the field of cutting edge technologies, such as information and communication technology, aerospace industry or military technology.

#### LEAD MARKETS AND COMPETITIVENESS OF LOCAL FIRMS

The existence of a domestic lead market and hence high demand with respect to quantity, but also to quality, allows supplying firms first to meet local demand, then to activate exports and eventually to provide products, processes and services to a broad range of users and on international markets.<sup>13</sup> Due to the market proximity local firms will be the first to notice the demand of new lead users. In detail the advantages can be grouped into:

- *Cost advantages.* Research and technology intensive industries are frequently characterized by economies of scale and scope. Hence, to benefit from the corresponding scale and scope effects in the form of cost degression, not only the current volume of domestic

demand but also the corresponding dynamics (the growth of demand) are important to assure international competitiveness. The positive scale effects are then magnified by the market volume.

- *Export advantages.* This summarizes effects such as representativity of domestic preferences for the world market, sensibility compared to changes of the demand conditions on the world market, the export ratio, but also linguistic and social compatibility with the advised market. Hence export advantages may arise if consumers on the home market prefer products and processes that have the potential to be successful also on other markets (see e. g. Beise 2001).

Firms in lead markets are the first to benefit from these advantages and this continuously secures a competitive advantage for innovative domestic firms (see e. g. Morrison, Roberts, and Midgley 2004)

#### ON THE ROLE OF PRIVATE DEMAND FOR CONTROVERSIAL TECHNOLOGIES

Inherent in innovative products and services is uncertainty. Therefore, individual risk attitude and risk perception become crucial for the actually existing private demand. The individual attitude towards technology and science also affect the preferences of domestic consumers. Individual openness towards new technologies is significantly affected by both anticipated utility and perceived risks. Slovic (1999) emphasizes that most notably the risk potential, its possible way to control it, the familiarity with risks and the public recognition determines how private individuals perceive innovations and hence drives demand for new products, processes or services. The following arguments gain especial importance:

- *Openness towards technology and science.* Inglehart (1997) states that a positive climate for innovation is the more probable, the more open-minded and tolerant a society is, since openness affects private demand for new products and services. Demand is at least in part affected by individual attitudes (openness towards new technologies, risk attitude – see below) as well as by norms that shape human interaction.<sup>14</sup> Basically, the society's openness is crucial for the innovation climate in certain regions and it also differs if considering certain types of technologies. Typically, differences may be identified with respect to controversial and non-controversial technologies. While for the latter, utility clearly dominates possible risk it is unclear in the case of controversial technologies whether risks

or opportunities prevail.<sup>15</sup> As a consequence these technologies are deeply ambivalent in the sense that strong opportunities go along with large risks.

- *Individual risk attitude.* Innovations are more likely to arise if the individuals are open-minded with respect to uncertainty. To operationalize the feature 'risk attitude' of private individuals usually the results from the Eurobarometer are used.<sup>16</sup> It regularly monitors on behalf of the European Commission the public opinion. In this context, positive indicators for innovation are preparedness to carry risks and preferences for self employment.
- *Trust in innovation actors (science, firms, and politicians).* Science and research are especially credible in countries having the following attributes: objective and differentiated commentatorship on risks and opportunities, high public acceptance of institutional frameworks, if people trust in and cooperate with other citizens and if politicians are perceived to follow rules of good governance.

Observe that a differentiated perception and assessment of opportunities and risks of new technologies is not per se negative for the development of new technologies. In contrast: A critical discussion may help develop the technology in a promising way. If doubts or reservations with respect to special applications are carefully considered by science, industry and policy and if the social and economic framework is chosen adequately it is possible to shape a climate that is open-minded and hence helps propagate innovation (see Hüsing 2002). As will be discussed below, this aspect gains especial importance in the context of controversial technologies.

### **An Application to Nanotechnologies**

#### NANOTECHNOLOGIES AS GENERAL PURPOSE TECHNOLOGIES

We now apply the argumentation detailed before on the case of nanotechnologies. They are perceived as being the next most important general purpose technology, and with this they are expected to affect economic and social life significantly within the next decades. The analysis begins with a brief illustration of why nanotechnologies actually qualify as general purpose technology, not only from a technological but also from an economic point of view. We then focus on the impact of demand, thereby relying on the argumentation carried out before.

*Pervasiveness and technological dynamics.* The generic function provided by nanotechnologies is its pervasiveness and the possibility to arrange single atoms. Nanotechnologies have huge potentials for improvement at the beginning of their development, are open to a multitude of possible uses, have an impact on nearly every part of economy and society, and can be embedded in already existing technologies. This causes major changes thereby affecting production structures, network relationships, and social differentiation. As such, nanotechnologies form part of technological platforms that organize future actions, and enable and constrain them (see research and development; also Robinson, Rip, and Mangematin 2006, 4ff.). Figure 1 demonstrates the interdependencies between several sectors, firms, and/or actors that utilize nanotechnologies within the production process. Looking at the simplest case, the hierarchical interdependencies as well as the network character are most suitably illustrated by a technology tree. Nanotechnologies represent the field of the general purpose technology. Since nanotechnologies are still at the very beginning of their technological development, further improvement is mostly provided by universities or research centers. This tempers the consequences of the appropriability effect discussed above in the sense that basic research in the field of nanotechnologies is financed by the public.<sup>17</sup> Both universities and research centers frequently provide the basis for spin-offs which end up in the development of components that may be used as inputs in the applying sector (AS). Hence applying sectors reflect the downstream industries that actually or potentially make use of the general purpose technology or augmented products as intermediates. Note that remarkable efforts are being made to close the gap between science and application. One prominent way is the foundation of institutions that act as a bridge between universities/research centers and firms.<sup>18</sup> Aside from vertical relationships, horizontal linkages exist between actors at the same level of the value chain.

In order to depict the development and implantation logics of nanotechnologies, let us give an example of a possible technology tree application. Nanotechnologies have many of applying sectors, such as, the chemical industry (AS 1), microelectronics (AS 2) or pharmacy (AS 3). New materials could be demanded by further downstream sectors such as aviation industries (AS 11, which use fire-resistant materials for in-board equipment), or automobile industries (AS 12, which use scratch-resistant lacquers).

*Innovational complementarities.* Additionally, ICT industries make

use of nano components to augment the calculating capacity of computers. Again, these are used by information technologies which have contributed significantly to the emergence of nanotechnologies. All illustrations of nano-scale effects and structures are based on digitally-constructed pictures. For more than thirty years, the capacity of computers has doubled every 12 to 18 months (Moore's law). However, within the next several years, physical boundaries will put an end to this development because, at nano-scales, the technological characteristics of solid state physics cease to hold and the usual transistor will be unusable. At this point, quantum physics will become relevant and molecules – manipulated by nanotechnologies – could replace the transistors known today. Consequently, technological progress in nanotechnologies becomes a precondition for future innovations in microtechnology, which anew spurs technological progress in the nanotechnologies sector.

*Reorganisation of work-life processes.* Applied to nanotechnologies, this argument is still diffuse because today these technologies are still at the very beginning of their development. But just to get a vague idea, one could imagine how, for example, intelligent materials that measure functions of the human body and transmit the results directly to medicine could enable people suffering from chronic illnesses to live their daily lives much less dependent on regular health checks or hospital visits.

These examples show quite plainly what one can easily observe within the field of nanotechnologies: the concrete and possible interactions within the technology tree require a lot of coordination, and consequently failures may arise.

#### DEMAND FOR NANOTECHNOLOGIES BY APPLYING SECTORS, AND CONSUMERS AND AGGREGATE EFFECTS

Although nanotechnologies are used at the very beginning of the value creation chain, at the end it is demand for final products that drives the demand for nano-intermediates. To facilitate the discussion we separate the two most important factors influencing demand, namely on the one hand, the price and the quality of the general purpose technology, and, on the other hand the utility derived by consuming a product that has been enhanced by nanotechnologies or that includes nano-intermediates.

*Firm demand.* As argued before innovations are too few and they arrive too late as a consequence of the prevailing externalities. Possibilities for internalization are at least twofold: At a vertical level the enforcement

of property rights gains importance. Here nano-patents may be a solution to spur innovation activities of firms along the entire value creation chain. On the other hand, horizontal externalities could be internalized by coordination of firms' demands that act at the same level of the value creation chain, e. g. firms in the aviation and the dockyards sectors could use the same scratch-resistant surfaces. Platforms for demand coordination could basically be provided by regional institutions.<sup>19</sup> If successful, demand in downstream sectors increases, thereby allowing for making use of economies of scale in the field of the upstream nanotechnology.

*Private demand.* Like biotechnology also nanotechnologies are *controversial technologies*. Hence it is not *per se* clear whether, from an individual point of view, chances or risks prevail. The individuals' attitude towards technology therefore is central. Werwatz et al. (2006; 2007) provide a ranking of attitudes and technology acceptances of citizens over 17 countries that could be used as a country's indicator for having the potential to become a lead market in a certain technology field.<sup>20</sup> Taking an overall look at attitudes and acceptance of all technologies, the following becomes obvious: Denmark, Sweden and Finland dominate the first three ranks, except for risk attitude, where Ireland, South Korea and the USA are ranked first. For most indicators, Austria, Ireland and Spain bring up the rear.

With respect to controversial technologies – and hence also with respect to nanotechnologies – the following conclusions can be drawn: Nearly 90% of the citizens in the considered countries assign a positive effect to non-controversial technologies, whereas with respect to controversial technologies this rate declines to 60%. It is also possible to differentiate between single countries: While people in the US are optimistic with respect to both controversial and non-controversial technologies, citizens in the Netherlands, Belgium, Sweden, Germany, Finland or UK strongly differentiate with respect to certain technology fields. Within these countries non-controversial technologies achieve the highest acceptance rate, with Germany being the leader. This means that Germans are very optimistic with respect to low-risk technologies, but this optimism clearly decreases in case of controversial technologies. This may hamper the development of nanotechnologies in the critical countries. In contrast, observe that this differentiated attitude may become an advantage in the long-run since a critical discussion may provide the design of new products or even political or institutional frameworks that foster future innovation activities. Thus, the critical scepticism in the short run



may provide the basis for becoming a lead market in the long run if, as a consequence of the initially detailed discussion, products are created that fit the needs of a large amount of consumers. Hence, this disadvantage with respect to regional competitiveness may turn to a future advantage.<sup>21</sup>

That attitudes towards technologies diverge across societies has also been extensively discussed in the context of the debate on the so-called NBIC (Nano-Bio-Info-Cogno) convergence:<sup>22</sup> NBIC-Convergence for Improving Human Performance is the name of a prominent agenda for converging technology research in the United States. In Canada, Bio-Systemics Synthesis suggests another agenda for converging technology research, whereas Converging Technologies for the European Knowledge Society (СТЕКС) designates the European approach. It prioritizes the setting of a particular goal for converging technology research. This presents challenges and opportunities for research and governance alike, allowing for an integration of technological potential, recognition of limits, European needs, economic opportunities, and scientific interests.

Long-run effects of nanotechnologies: Nanotechnologies are expected to introduce the next long-run wave, thereby providing continuous incentives for incremental innovation. As discussed before, it is inherent to general purpose technologies that their impact on overall productivity becomes significant only after sufficient complements are in the market and after the completion of important adjustment processes. Hence, although the recent market potentials of nanotechnologies are already immense, it will probably take several years or even decades until overall productivity has increased as a consequence of the use of the new general purpose technology.

### **Summary and Conclusions**

This paper investigates the implications of innovation processes in the context of nanotechnologies. The focus as well as the corresponding discussion is twofold: nanotechnologies and their implications are analyzed as controversial and as general purpose technologies, thereby disentangling supply-side and demand-side arguments. As a drastic innovation, nanotechnologies induce innovation processes in downstream sectors which – due to feedback effects – in turn affect productivity and with this innovation in the upstream nanotechnologies. The analysis is carried out with special attention to supply-side and demand-side arguments. Since nanotechnologies are utilized at the very beginning of the value

creation chain it is necessary to disentangle different parts of total demand into firms' demand for nano-components and private demand for final products. With respect to the firms' demand the following gains importance: Innovation processes are interrelated along the value creation chain, and feedback mechanisms work in both directions: upstream and downstream. Due to the appropriability effect, innovating firms are not able to appropriate all benefits that are induced by their innovation activities. As a consequence, innovations arise too late and their extent is too low. On the other hand, nanotechnologies are highly controversial among consumers and it is not *per se* clear whether opportunities or risks in the use of final products that are augmented by nanotechnologies dominate. This again may hamper innovations in the fields of nanotechnologies, and the individual's attitude towards risk and technology becomes especially important. Both individual and firm's demand hence may be sub-optimally low with respect to a harmonized innovation process. However, interventions in the innovation process carefully have to consider at which level of the value chain they are realized.

### **Acknowledgments**

The authors gratefully acknowledge financial support from the Volkswagen Foundation, funding initiative Innovation Processes in Economy and Society, grant no. 11/83 568. Constructive comments by two anonymous referees helped improve the paper significantly.

### **Notes**

- 1 The incremental nature of technological process has been well documented by economic historians (see e. g. Rosenberg 1992).
- 2 Examples for an exchange of technology could be the replacement of horse power by electricity or, in the case of products, the replacement of rubber or steel by plastics.
- 3 However it is not trivial to identify possible discontinuities in the empirical data. A recent discussion about the state of the art and possibly arising problems can be found e. g. in Christiansen (2008).
- 4 Hence governmental demand is most important to spur innovation in the field of drastic innovations, while private demand may well suffice for incremental innovations. However, this paper refrains from dealing with a sophisticated discussion of the role of governmental demand.
- 5 In the following parts the abbreviation GPT stands for general purpose technology.

- 6 Note that other authors, e. g. Lipsey, Bekar, and Carlaw (1998) define general purpose technologies slightly different. For example these authors stress the importance that at their emergence general purpose technologies are characterized by a wide potential of improvement, hence inducing technological dynamics.
- 7 The emergence of electricity, e. g., made people independent from daylight. This had far reaching consequences for the organization of work life – and hence also affected the daily routines not only of firms but also of families.
- 8 Bresnahan and Trajtenberg (1995) call this ‘dual inducement hypothesis’.
- 9 See Bresnahan and Trajtenberg (1995) for a formal presentation of these interdependencies.
- 10 Note especially the literature in the context of so called basic innovations which induce long-run waves which sometimes are also called Kondratieff cycles; observe also the argumentation in Rosenberg (1996) or David (1990).
- 11 Observe that one could basically extend the analysis also with respect to the role of complementary investment of any kind.
- 12 This topic is discussed in detail within the literature on industrial organization. An overview can be found e. g. in Tirole (1990). The corresponding impact on aggregate growth is discussed e. g. by Aghion and Howitt (1998), Grossman and Helpman (1990) or Barro and Sala-i-Martin (2004).
- 13 Some typical examples for lead markets are the us for personal computers or drugs, Japan for fax and video, or Scandinavian countries for mobile telephones. Germany is a typical lead market in automobile or process technology. The latter includes mechanical engineering, measurement technology, environmental technology and technical components. The lead position is based on a strong industrial basis as well as mostly on the preferences of industrial customers.
- 14 For some technologies, e. g. telecommunication or the internet, network effects also gain importance. Then the level of individual utility increases with the number of people using the same technology.
- 15 Non-controversial technologies are solar energy, new propulsion technologies or medicine. Controversial technologies are biotechnology, nanotechnology or high-tech agriculture (see e. g. Werwatz et al. 2007).
- 16 Central features of the Eurobarometer include questions about health, culture, information technologies, environmental protection, the Euro or national defense. More information can be found at [http://ec.europa.eu/public\\_opinion/index\\_en.htm](http://ec.europa.eu/public_opinion/index_en.htm).
- 17 A detailed discussion about financing details in the context of basic research and applied research can be found in Klodt (1995).

- 18 Examples for such institutions are CAN in Hamburg or MINATEC in Grenoble.
- 19 See e. g. Ott and Papilloud (2007) for an analysis of a regional institution's impact on the development of nanotechnologies.
- 20 The following countries are included: Sweden, Finland, Denmark, The Netherlands, USA, UK, Canada, Belgium, Japan, South Korea, Ireland, Spain, Germany, Switzerland, France, Italy and Austria. The indicators focus on questions with respect to: (i) openness towards technology and sciences, (ii) basic attitudes according to Inglehart (1997), (iii) risk attitude, (iv) trust in innovation actors, and (v) women's participation rate.
- 21 Observe that more knowledge and scientific understanding does not generally lead to higher acceptance of technologies and innovation. While knowledge increases acceptance of non-controversial technology, this result does not hold for controversial technologies. Evans and Durant (1995) show that more knowledge raises the acceptance gap between different technology fields. Hence increasing knowledge does not automatically spur acceptance rates of controversial technologies.
- 22 See Nordmann (2004, 19), and also Roco and Bainbridge (2002, 282). Defending a strict technological classification of the expression converging technology, Roco and Bainbridge (2002, 282) refer it to the combination of four major NBIC proveniences of science and technology, namely, (1) nanoscience and nanotechnology; (2) biotechnology and biomedicine, including genetic engineering; (3) information technology, including advanced computing and communications; and (4) cognitive science, including cognitive neuroscience. For a broader application of this expression, compare the description given by Wood, Jones, and Geldart (2003, 23): 'Many of the applications arising from nanotechnology may be the result of the convergence of several technologies.'

## References

- Acemoglu, D. 2009. *Introduction to modern economic growth*. Princeton, NJ: Princeton University Press.
- Aghion, P., and P. Howitt. 1998. *Endogenous growth theory*. Cambridge, MA: MIT Press.
- Barro, R., and X. Sala-i-Martin, 2004. *Economic growth*. Cambridge, MA: MIT Press.
- Beise, M. 2001. *Lead markets: Country-specific success factors of the global diffusion of innovations*. ZEW Economic Studies 14. Heidelberg: Physica.
- Beise, M., and T. Cleff. 2004. Assessing the lead market potential of countries for innovations projects. *Journal of International Management* 10 (4): 453–77.

- Blümle, G. 1994. The importance of environmental policy for international competitiveness. In *Interactions between economy and ecology*, ed. T. Matsugi and A. Oberhauser, 35–57. Berlin: Springer.
- Bresnahan, T., and M. Trajtenberg. 1995. General purpose technologies: Engines of growth. *Journal of Econometrics* 65 (1): 83–108.
- Christiansen, L. E. 2008. Do technology shocks lead to productivity slowdowns? Evidence from patent data. IMF Working Paper WP/08/24.
- David, P. A. 1990. The dynamo and the computer: An historical perspective on the modern productivity paradox. *American Economic Review* 80 (2): 355–61.
- Evans, G., and J. Durant. 1995. The relationship between knowledge and attitudes in the public understanding of science in Britain. *Public Understanding of Science* 4 (1): 57–74.
- Fagerberg, J. 1995. Technology and competitiveness. *Oxford Review of Economic Policy* 12 (3): 39–51.
- Gerybadze, A., F. Meyer-Kramer, and G. Reger. 1997. *Globales Management von Forschung und Entwicklung*. Stuttgart: Poeschel.
- Grossman, G., and E. Helpman. 1990. *Innovation and growth in the global economy*. Cambridge, MA: MIT Press.
- Helpman, E., and M. Trajtenberg. 1998. A time to sow and a time to reap: Growth based on general purpose technologies. In *General purpose technologies and economic growth*, ed. E. Helpman, 55–83. Cambridge, MA: MIT Press.
- Hüsing, B., R. Bierhals; B. Bührlen, M. Friedewald, S. Kimpeler, K. Menrad, J. Wengel, R. Zimmer, P. Zoche. 2002. Technikakzeptanz und Nachfragemuster als Standortvorteil: Abschlussbericht. Karlsruhe: Fraunhofer ISI.
- Inglehart, R. 1997. *Modernization and postmodernization*. Princeton, NJ: Princeton University Press.
- Klodt, H. 1995. *Grundlagen der Forschungs- und Technologiepolitik*. München: Vahlen.
- Linder, S. B. 1961. *An essay on trade and transformation*. Uppsala: Almqvist & Wicksells.
- Lipsey, R., C. Bekar, and K. Carlaw. 1998. What requires explanation? In *General purpose technologies and economic growth*, ed. E. Helpman, 55–83. Cambridge, MA: MIT Press.
- Morrison, P. D, J. H. Roberts, and D. F. Midgley. 2004. The nature of lead users and measurement of leading edge status. *Research Policy* 33 (2): 351–62.
- Nordmann, A. 2004. *Converging technologies: Shaping the future of the European societies*. Brussels: European Commission.
- Ott, I., and C. Papilloud. 2007. Converging institutions: Shaping relation-

- ships between nanotechnologies in economy and society. *Bulletin for Science, Technology & Society* 27 (6): 455–66.
- Robinson, D. K, A. Rip, and V. Mangematin. 2006. Technological agglomeration and the emergence of clusters and networks in nanotechnology. Working Paper GAEL 2006-5.
- Roco, M. C., and W. Bainbridge. 2002. Converging technologies for improving human performance: Integrating from the nanoscale. *Journal of Nanoparticle Research* 4 (4): 281–95.
- Rosenberg, N. 1992. *Inside the black box*. Cambridge: Cambridge University Press.
- . 1996. Uncertainty and technological change. In *The mosaic of economic growth*, ed. R. Landau, T. Taylor, and G. Wright, 334–53. Stanford, CA: Stanford University Press.
- Slovic, P. 1999. Trust, emotion, sex, politics, and science: surveying the risk-assessment battlefield. *Risk Analysis* 4 (19): 689–700.
- Tirole, J. 1990. *The theory of industrial organisation*. Cambridge, MA: MIT Press.
- Werwatz, A., H. Belitz, T. Kirn, and J. Schmidt-Ehmcke. 2006. *Innovationsindikator Deutschland 2006*. Berlin: DIW.
- . 2007. *Innovationsindikator Deutschland 2007*. Berlin: DIW.
- Wood, S., R. Jones, and A. Geldhart. 2003. *The social and economic challenges of nanotechnology*. London: Economic and Social Research Council.