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# INDUSTRIAL RENEWAL AND GROWTH THROUGH NANOTECHNOLOGY?

## – An overview with focus on Finland*

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**PALMBERG,** Christopher – **NIKULAINEN**, Tuomo, **INDUSTRIAL RENEWAL AND GROWTH THROUGH NANOTECHNOLOGY? – AN OVERVIEW WITH FOCUS ON FINLAND**. Helsinki: ETLA, Elinkeinoelämän Tutkimuslaitos, The Research Institute of the Finnish Economy, 2006, 45 p. (Keskusteluaiheita, Discussion Papers, ISSN 0781-6847; No. 1020).

**ABSTRACT:** Hardly any other field has received so much public R&D investments globally in such a short time as nanotechnology. Nanotechnology can be considered as an umbrella term for R&D at the nanometer scale (1-100 nm) where unique phenomena enable novel applications. The interest given to nanotechnology is largely due to its perceived, and partly also over-hyped, generic nature and potentials to renew industries in a revolutionary way. Nonetheless, the field is still in a fluid and nascent phase without clear indications of how and where commercial breakthroughs will emerge on a larger scale. This paper aims to conceptualize nanotechnology in the literature on the economics of technological change, review the extant empirical research towards this end, and provide a brief overview and new insights into the development of nanotechnology in Finland. It discusses to what degree nanotechnology fits the criteria of a general purpose technology (GPT) and, in this context, highlights some important issues related to technology transfer, industrial dynamics and organisation. The case of Finland is interesting due to recent and relatively significant nanotechnology policy initiatives and the competitive position that it holds in many traditional industries. Although new firms also are emerging, Finnish nanotechnology primarily appears to be driven by scientific developments and the role of large firms is still small. Patenting is picking up from a low level, and process engineering and chemicals are emerging as the main application fields.

**KEYWORDS:** nanotechnology, general purpose technology, industrial renewal, Finland
**JEL-codes: 032, 033, 040**

**PALMBERG,** Christopher – **NIKULAINEN**, Tuomo, **TEOLLISUUDEN UUDISTUMINEN NANOTEKNOLOGIAN AVULLA? – KATSAUS ALAN KIRJALLISUUTEEN SUOMEN NÄKÖKULMASTA**. Helsinki: ETLA, Elinkeinoelämän Tutkimuslaitos, The Research Institute of the Finnish Economy, 2006, 45 s. (Keskusteluaiheita, Discussion Papers, ISSN 0781-6847; No. 1020).

**TIIVISTELMÄ:** Tuskin mihinkään muuhun teknologiaan on investoitu niin lyhyessä ajassa yhtä paljon T&K rahoitusta kuin nanoteknologiaan. Nanoteknologialla tarkoitetaan yleensä toiminnallisesti uudentyyppisiin materiaaleihin ja nanomittakaavaan (1-100nm) rakenteisiin perustuvien komponenttien ja laitteiden suunnittelemista ja valmistamista eri-tyyppisiin sovelluksiin. Nanoteknologia nähdään geneerisenä yleiskäyttöisenä teknologiana jolla uskotaan olevan potentiaalia merkittävästi uudistaa useiden teollisuuden alojen toimintaa. Kehitys on kuitenkin vielä varsin varhaisessa vaiheessa ja on vielä epäselvää millä tavalla ja mihin suuntaan nanoteknologia kehittyy, varsinkin applikaatioalueiden ja kaupallistamisväylien näkökulmasta. Tämän työpaperin tarkoitus on jäsentää nanoteknologia innovaatiotutkimuksen ja taloustieteen kirjallisuuden ja olemassa olevien tutkimusten kautta sekä tuottaa uutta tietoa Suomen nanoteknologian kehityksestä. Paperissa pohditaan pystyykö nanoteknologia todellakin kehittymään yleiskäytölliseksi teknologiaksi sekä miten nanoteknologia voisi kaupallistua. Suomessa investoidaan myös suhteellisen paljon nanoteknologiaan. Joitakin uusia yrityksiä on jo syntynyt mutta kehitys on vielä vahvasti tiedevetoinen ja suuryritysten rooli on vielä vähäinen. Tämä näkyy erityisesti nanoteknologia-julkaisujen voimakkaana kasvuna sekä patentoinnin vähäisessä määrässä. Applikaatioalueita on pääasiallisesti syntymässä prosessi- ja kemian teollisuudessa.

**AVAINSANAT:** nanoteknologia, yleiskäyttöiset teknologiat, teollisuuden uudistuminen, Suomi
**JEL-koodit: 032, 033, 040**

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# 1. INTRODUCTION

## 1.1. Background

So called general-purpose technologies play an increasingly important role for the competitiveness of industrialised countries. As the name suggests general purpose technologies are characterised by their potential widespread use to renew traditional industries and create new ones. They require a range of complementary technological and organisational innovations, but once such general purpose technologies diffuse throughout economies they can function as the 'engines of growth' for extended periods of time. Steam power and electricity are commonly used examples of such technologies. There is also mounting empirical evidence that information and communications technology (ICT) has similar characteristics, and some commentators also point to the potentials of modern biotechnology in this context (Freeman and Perez, 1988; Helpman, 1998; Jovanovic and Rousseau, 2005).

As the examples of ICT and modern biotechnology suggests general purpose technologies have long incubation times before they reach the momentum required for becoming new engines of growth. Nonetheless, governments in many industrialised countries eagerly search for, and seek to support the development and diffusion of, these types of technologies to prepare themselves for tightening global competition and the next phases of industrialization. The most recent example is nanotechnology as an umbrella term for R&D at the nanoscale.[1] In fact, hardly any other technology field has attracted so much public funding globally in such a short time as has been the case with nanotechnology and private funding is also picking up rapidly (Lux Research, 2006). The attractiveness of nanotechnology primarily relates to its highly generic nature and – partly also over-hyped – potentials to renew existing manufacturing processes, products, services and industries in a revolutionary way. Hence, countries and regions around the world now seek to establish leading positions in this field.

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[1] The term nanotechnology refers to the understanding and control of matters at the 1 to 100 nanometer scale where unique phenomena enable novel applications. It will be defined in greater detail further on.

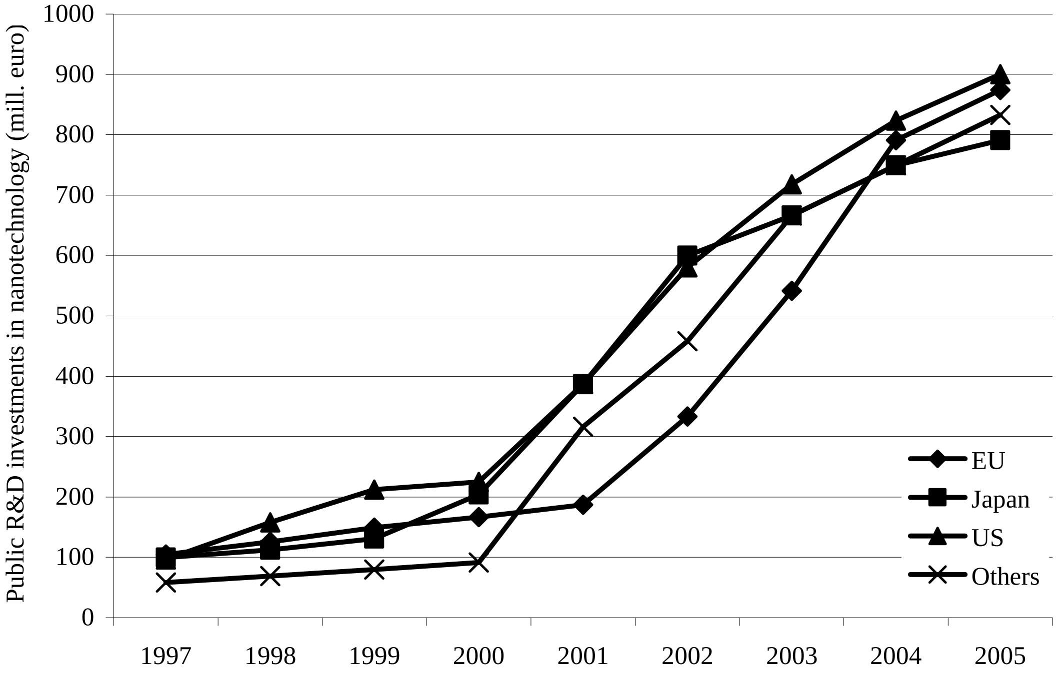

Figure 1. Estimated public nanotechnology R&D investments

Source: PCAST (2005)

Figure 1 illustrates the rapid growth of public R&D funding for nanotechnology, as defined by the US National Nanotechnology Initiative, across the European Union (EU), Japan, US and other industrialized countries lumped together. By these estimates funding increased worldwide over eightfold during the period from 1997 to 2005. The EU Commission has drawn up a coordinated strategy towards nanotechnology. When the EU figures are broken down by countries it becomes clear that the smaller highly industrialised countries also are investing large sums into this new field. Further, the Nordic Innovation Centre is also activating itself with the aim of enhancing the competitiveness of firms throughout the Nordic countries through the application of nanotechnology (EU, 2004; Nordic Innovation Centre, 2006).

Nanotechnology is an interdisciplinary and science-based field that poses big challenges especially for small countries with limited resources. In Finland nanotechnology might be an especially interesting field due to it's potential to leverage R&D and thereby add value to existing strongholds especially in traditional and maturing industries where global price competition is strongest. On the other hand, nanotechnology also demands absorptive capability, new expensive research facilities, instrumentation and the development of new commercialization avenues at the interfaces between industrial application and top-level scientific research. It is not self-evident that previous Finnish successes and capabilities in the development and production of ICT will be transferable to the field of nanotechnology (compare with Palmberg and Luukkonen (2006)). As a new field nanotechnology differs in many important ways both from ICT and modern biotechnology. It still in a very fluid and nascent phase and it is unclear where the most viable applications areas and commercialisation avenues for this technology are to be found. Apart from the hype and the technical literature there is very little substantial analysis on the economic significance of nanotechnology and on its potential to renew existing industries. Such analysis is especially important in a small country context where the risks of misguided R&D investments are the highest.

## 1.2. Aim and structure

This paper is intended to anchor the development of nanotechnology in the broader theoretical and conceptual framework of the economics of technological change. It also provides a review of the meagre but expanding empirical literature in this field, and presents some first analysis of the development of nanotechnology in Finland. More concretely, its aims might be summarized in terms of the three following questions:

1. What is nanotechnology, how has it developed, and how can the economic significance and potentials of this technology field be conceptualized in the theoretical literature on the economics of technological change?
2. How has extant research within this literature approached nanotechnology and which main empirical observations are emerging to characterise the nature, development, economic significance and effects of this emerging technology field?
3. Where does Finland stand in nanotechnology in international comparisons, which types of public sectors activities are emerging to support nanotechnology, and how is the related activity reflected in the science and technological developments as viewed by patent and publication data?

As has been suggested already, nanotechnology – as is typical in the case of the emergence of new fields that suggest enormous commercial potential – is subject to a great deal of hype and science-fiction-type of speculation. The emergence of nanotechnology is also giving rise to a burgeoning and important technology assessment, forecasting and ethical discussions on how this technology should be regulated and use (see e.g. Langlais et al., 2004). It should be made clear at the outset that this paper, as well as the underlying research project, will limit itself to an analysis of nanotechnology in the tradition of the economics of technological change.

The paper is structured as follows. Section 2 starts off with a discussion of the definition of nanotechnology and a brief overview of milestones of the emergence of this new technology field. Section 3 turns to extant theoretical conceptualizations within the economics of technological change that might be useful in understanding nanotechnology, blended with an overview of extant empirical research on the nature and development of this technology field. Sections 4 and 5 turn to the case of Finland to assess its position in nanotechnology from an international viewpoint, identify public policy initiatives, research and firm communities in this new technology field. Section 6 synthesizes the paper and identifies research issues to be tackled during the course of the project.

## 2. NANOTECHNOLOGY AND ITS DEVELOPMENT

### 2.1. Definining nanotechnology

As is often the case with generic technologies, definitions and delimitations of what comprises of nanotechnology are much disputed amongst scientists and engineers. Some claim that it represents a relatively coherent set of technologies that together mount to a new knowledge base that fundamentally challenges, and even disrupts, extant scientific and engineering principles. Others suggest that nanotechnology is a hype-word rather than a new technology in the sense that it merely redefines existing research agendas, and thus mostly enhances knowledge bases that scientists and engineers already draw upon (Andersen, 2005). This discussion is ongoing and we will not dwell any further into it. Instead it makes sense to highlight a pragmatic definition of nanotechnology that is much referred to and useful also in our context.

On a very general level nanotechnology refers to new approaches to R&D that aims to control the fundamental structure and behaviour of matter at the level of atoms and molecules. This emphasis on smallness is reflected in the term 'nano' which refers to a microscopic measurement scale where 1 nanometer (nm) measures a millionth of a millimetre. Correspondingly, 100 nm measures a thousandth of a millimetre. For comparison, the thickness of human hair roughly corresponds to 50 000 nanometers. Precisely this smallness is also the clue to the scientific, technological and economic significance of nanotechnology. When the size of material approach the nanoscale they start to obey quite different laws of physics, based on quantum mechanics, and thus gain completely new – and as of yet less understood – properties in terms of chemical reactivity, optical, electronic and magnetic behaviour. This, in turn, means that materials potentially can find a range of new applications and uses throughout a very large number of industries (Hassan and Sheehan, 2003; Hall, 2005).

The surge in public R&D investment in nanotechnology has implied that pragmatic definitions of nanotechnology have been developed to set R&D agendas. They have usually also centred on the measurement scale as a means of delimiting the type of R&D that falls into the nanotechnology category, while likewise stressing the importance that this R&D is directed towards new functionalities and applications of materials. In the history of public R&D funding for nanotechnology the National Nanotechnology Initiative (NNI) in 2001 in the US can be considered an important milestone due to its volume in terms of funding as well as the size and centrality of the scientific and engineering capabilities of the US R&D system (Ratner and Ratner, 2003). The definition of nanotechnology that this initiative uses has become the most often referred to in policy circles and it will also be our point of departure:

> *"Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale." (http://www.nano.gov)*

This definition requires some additional clarification. The "understanding and control of matter" at the nanoscale refers to the rearranging molecules so that essentially every atom can be put in its most efficient place so as to achieve a particular functionality. Nanotechnology is thus primarily a new production method that enables new product innovations. Further, nanotechnology is considered to encompass both the scientific knowledge base upon which it draws, as well as the engineering and technological activities that contribute to applications and commercialisation of this technology. This definition thereby highlights the very close linkages between scientific and technological developments that characterises this field (see e.g. Meyer (2000)).

The science-base of nanotechnology is very interdisciplinary as it combines various subfields of physics and chemistry in its extension of the material sciences. Nanotechnology is also often associated with modern biotechnology, especially in some of the more futuristic scenarios (Hall, 2005). On the engineering side one might identify two basic approaches, namely the 'top-down approach' and the 'bottom-up' approach. The former approaches existing materials at the nanoscale through traditional lithography, cutting, etching or grinding techniques. Examples include various electronic devices, computer chips, MEMS or optical mirrors of very high quality. The latter approach actually creates new materials at the nanoscale through chemical synthesis or self-assembly of particle molecules and their macrostructures, such as crystals, films or tubes. Of these, the top-down approach has hence-far been the more common while the bottom-up approach still faces many bottlenecks to overcome (Andersen, 2005; Hall, 2005).

## 2.2. Milestones and commercialisation avenues

Conceptually nanotechnology was identified by the physicist Richard Feynman in his seminal talked from 1959 at the American Physical Society Meeting at the Californian Institute of Technology (Caltech) entitled "There is plenty of room at the bottom". In this documented talk he anticipated the possibility of controlling matter at a nanoscale and thus introduced the scientific community to a new hypothetical field of enquiry that had not really been thought of before. The term "nanotechnology" was first defined by Norio Tangichi in 1974 from the Tokyo Science University, while the basic idea of this technology was explored in greater detail by Eric Drexler, a graduate from Massachusetts Institute of Technology who founded the field of molecular nanotechnology. In 1992 he published "Engines of Creation – The Coming Era of Nanotechnology", which has been much referred to especially in the more scary scenarios of where nanotechnology might develop.

Nonetheless, there is significant consensus amongst scientist that nanotechnology really took of in the early 1980s due to the development of enabling inventions in the field of microscopy. A milestone in this context was the Scanning Tunneling Microscope (STM) in 1981 (US Patent nro. 4343993) which was invented by Gerd Binning and Heinrich Rohrer at the IBM Research laboratory in Zurich. The STM enables atomic-scale images of metal and semiconductor surfaces that could not be obtained by previous microscopes. The range of materials that could be tunnelled with the STM increased significantly through the invention in 1986 of the Atomic Force Microscope (AFM) (US Patent nro. 4724318) again by Gerd Benning and his colleagues at IBM. The significance of these inventions is highlighted further by the fact that they received the Nobel prize in 1986 (Lämsä, 2003; Bonaccorsi and Thoma, 2005).

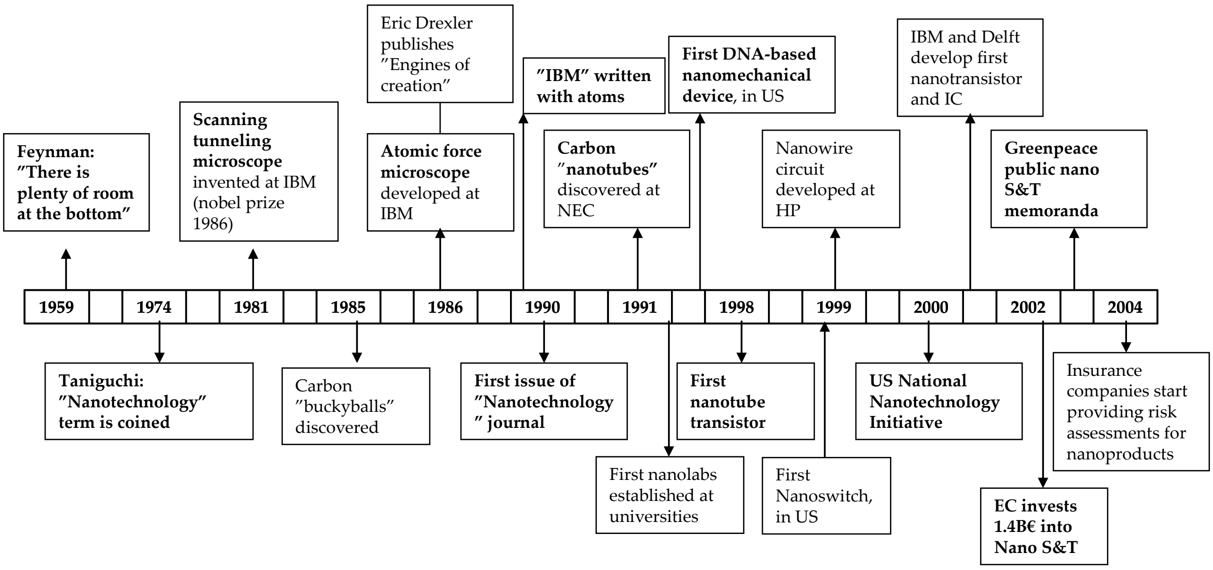

Figure 2. Milestones in the development of nanotechnology

The economic significance of these inventions are due to the fact that they codified much of the know-how of nanotechnology at the time, and thus contributed to the worldwide diffusion of basic nanotechnology techniques. They represented "inventions of a method of inventing" and – together with a range of complementary inventions – offer a necessary springboard for the possible commercial breakthrough of nanotechnology on a broader scale (Darby and Zucker, 2003). In the 1990s further enabling inventions were made with applications. Some of the more noteworthy ones include carbon nanotubes for applications in new materials, nanotube transistors and nanowire circuitry for applications in the electronics industry. The US National Nanotechnology Initiative in 2001 can also be considered a milestone in terms of public investments in nanotechnology, while the EU became involved with significant investments starting from 2002.

Despite these enabling inventions and other developments it is clear that nanotechnology still is in a very fluid and nascent phase of development and has not yet reached a clearly defined commercial breakthrough. Even though every-day nanoproducts indeed are becoming available on the market nanotechnology still lags behind especially ICT but also modern biotechnology that already has scored some success (Zucker and Darby, 2005; Forbes Nanotech Report, 2005).

Despite the immaturity of nanotechnology it is possible to identify specific application areas and commercialization avenues, some of which are contributing to the formation of a rudimentary value chain and related industrial organisation. The industrial fields of ICT, electronics, new materials, health and life sciences appears as those where firms are connecting to nanotechnology and drawing up strategies for introducing innovations with nanoscale functionalities. Examples include memory chips that further boost data processing and storage capacity, new types of nitrides, oxides, alloys, metals, organic polymers and composites of relevance in aerospace, medicine, building and construction, as well as precision drugs. Nanotechnology might also soon play an important role in the field of renewable energy through the improvement in the efficiency off photovoltaic cells, and it finds a range of applications in the military sector (Ghadar and Spindler, 2005).

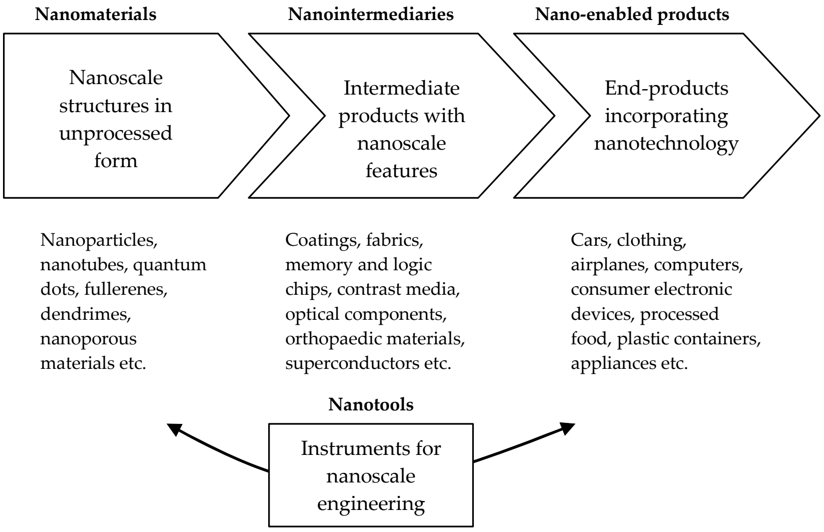

Figure 3. The emerging value chain in nanotechnology

Source: Luxresearch (http://www.luxresearchinc.com)

Luxresearch, a major consultancy in the field, has attempted to sketch the boundaries of an emerging value chain in nanotechnology to analyse emerging business opportunities (Figure 3). The first upstream segment of the value chain comprises of nano raw-materials such as so-called carbon nanotubes, quantum dots and dendrimers. Even though research continues around these raw-materials they are already available on the markets at reasonable costs. This segment is thus also the most competitive one and already partly dominated by the larger countries such as the US, Japan and China.

The next segment further downstream comprises of intermediate products at a nanoscale that can be used as components in end-products in the last segment of the value chain. This segment is the most dynamic at present and is mainly populated by new start-ups. Examples of products include coatings, memory chips, optical components, superconducting wire etc. The last segment comprises of end-products incorporating nanotechnology, and it is mainly populated by large and established firms (incumbents). In this segment one might potentially find a very large number of different products with embedded nanoscale functionalities, ranging from cars, clothing, computers, consumer electronics to precision drugs and various other medical applications.

Apart from these segments the development of various nanotools as enabling instruments for conducting nanoscale engineering, is also acknowledged as an area with business potentials. In the backwaters of the invention of STM and AFM microscopy numerous smaller firms are also entering this field.

# 3. THE ECONOMICS OF NANOTECHNOLOGY

## 3.1. General purpose technologies

As already suggested economists have coined the concept "general purpose technologies" (henceforth referred to with the acronym GPT) to incorporate broad-based technologies, such as steam power, electricity, and ICT, into analysis of economic growth (Koski, 2005; Jovanovic and Rousseau, 2005). The usefulness of this concept comes with theoretical models that have been developed to better understand under which conditions and how GPTs might turn into the engines of growth for extended periods of time. Economists have for a long time recognized that technical change is the single most important force behind growth (see Verspagen (2005) for a recent review). Still formal theories have not sufficiently accounted for differentiated effects of different types of technological change. The concept GPT, and the related models, have been introduced to cater to this deficiency, the prime reference here being Bresnahan and Trajtenberg (1995), and Helpman (1998).

A GPT consists of a basic 'breakthrough' technology that is dependent on a range of complementary incremental technological and organisational innovations for its diffusion and ultimate effects. Similar to new growth theory, pioneered by Romer (1986), the growth effects of a GPT arise through a new supply of an ever-expanding range of capital goods, but this time specific to the GPT in question. In the formal models that have been developed in this tradition, a GPT emerges exogenously but becomes endogenous to the economic system through diffusion and usage in various firms and industries as complementary incremental innovations emerge (Helpman, 1998). Hence, the ultimate effects of a GPT on growth will not only depend on its intrinsic technological characteristics. It will also depend on the degree to which usage patterns, firms, infrastructures, public policy, regulations and other institutional arrangements are conductive for technology diffusion. As a result, the growth effects typically manifest themselves in alternating periods of slowdown and acceleration in productivity as the examples of both electricity and ICT suggests (Jovanovic and Rousseau, 2005).

The ideas of breakthrough technologies, the significance of complementary incremental innovations, facilitating economic and institutional contexts, and alternating phases of technology-driven economic growth are certainly not new. Similar insights are frequent in the Schumpeterian and evolutionary tradition of economics going back to Joseph Schumpeter (1911, 1942) and Nelson and Winter (1982)(see Fagerberg (2003) for a recent review). From the viewpoint of this paper the merits of the literature on GPT stems from the way in which it can be related to economic growth. Further, the literature offers an interesting and relevant discussion of necessary – albeit not sufficient – characteristics for a technology field to evolve into a GPT.

An elaborate discussion of the characteristics of GPTs is found in Lipsey et al. (1998). At the outset they acknowledge that technologies typically come in bundles due to various interrelations between core and complementary technologies, and often comprise of whole technological systems (compare with the discussion in Freeman and Perez (1988)). They also note that a GPT might, in its early development phase, be exogenous to the economic system while being endogenous to the science system. A GPT might therefore not initially be guided by profit-seeking decisions as often is the case in a university environment, although it needs to become so in order to contribute to growth. Further, they acknowledge that GPTs usually build incrementally on existing technological systems even though their ultimate effects might be radical (compare also to the discussion in Carlsson et al. (2002)). Beyond these general characteristics Lipsey et al. (1998) identify four somewhat more precise necessary criteria for a GPT.

First, a GPT has to have *significant scope for improvement* along economically relevant dimensions of merit so that its cost of operation will fall over time. Related to this, the second criterion is that a GPT has *a widening variety of uses* as it develops and the costs decline. In other words, it finds application in an increasing range of products and processes throughout different sectors of the economy. Third, it also has to find a *range of different uses* in the sense that a large share of the production activity in the economy uses the technology. Fourth and finally, it has to generate, and will also for its diffusion depend on, a range of other *new complementary technologies and innovations*. When these four necessary criteria for a GPT are considered jointly it is relatively easy to identify both electricity and ICT as GPTs. In particular, the price of ICT technologies have indeed dropped significantly over time, while their variety and range of usage successively has broadened to most industries and productive activities in the economy. Further, ICT is generating complementary innovations both in terms of technologies and organisations, although the productivity effects and adaptability of different economies to ICT are debated (Koski, 2005).

### 3.2. Could nano become a general purpose technology?

Our discussion hence far in this paper suggests that nanotechnology still is in a very fluid and nascent phase of development, also when compared with modern biotechnology. Nonetheless, given the attractiveness of the technology field, especially in the eyes of public funders in most industrialised countries, it makes sense to step back and proactively pose the question whether nanotechnology might be a candidate for a GPT of the future. A pondering of this question can also contribute to a better appreciation of the specificities of nanotechnology, especially in the context of innovation policy. To what degree, then, could the four necessary criteria of a GPT also describe nanotechnology as it is emerging?

When considering each of the four criteria in turn, some perspective on the first criterion of the *significant scope for improvement* can be gained by looking at nanotechnology patenting as an indicator of perceived technological opportunities judged as commercially viable. Again an interesting comparative field is modern biotechnology where developments took off at an accelerating pace some 13 years after breakthroughs in genetic engineering in 1973 after which patenting of genetic sequences became possible and commercially lucrative. If this incubating period for technological breakthroughs is translated to nanotechnology developments the acceleration of nanotechnology patenting should have occurred some five years ago at the turn of the century, or some 13 years after the invention of the Scanning Tunneling Microscope (STM) and the Atomic Force Microscope (AFM) (Darby and Zucker, 2003).

Recent analysis of global nanotechnology patenting indeed shows accelerating growth with a significant lag following the basic enabling inventions. Using relevant keyword matches of the entire full text fields of patents, Huang et al. (2004) identify as many as 70 039 granted US patents to trace worldwide developments in nanotechnology. They identify a strong upward trend after 1997, accelerating further after 2000 with a growth rate of 50%. This exceeds the growth rate of 4% for patenting in all other fields. Interestingly patenting starts already in 1976 prior to the invention of STM and AFM microscopy, thus underlining that the concept nanotechnology also largely redefines existing research agendas.

Further, the distribution of patents is highly skewed across countries, pointing to the dominance of the US as a major developer of nanotechnology. US assignees accounted for 61%, followed by Japan with 9%, Germany with 8%, Canada and France with 3% (compare also to Marinova and McAleer (2002)). Korea, Holland, Ireland and China are the countries which have experienced the fastest growth in the number of nanotechnology patents in recent years. Nonetheless, it should be noted that the absolute numbers of nanotechnology patents should be judged with great care as the numbers depend critically on the specific definitions of nanotechnology as well as whether full text searches or only title and keyword searches are used. Keyword search algorithms related to nanotechnology are still in need of further development and refinements.

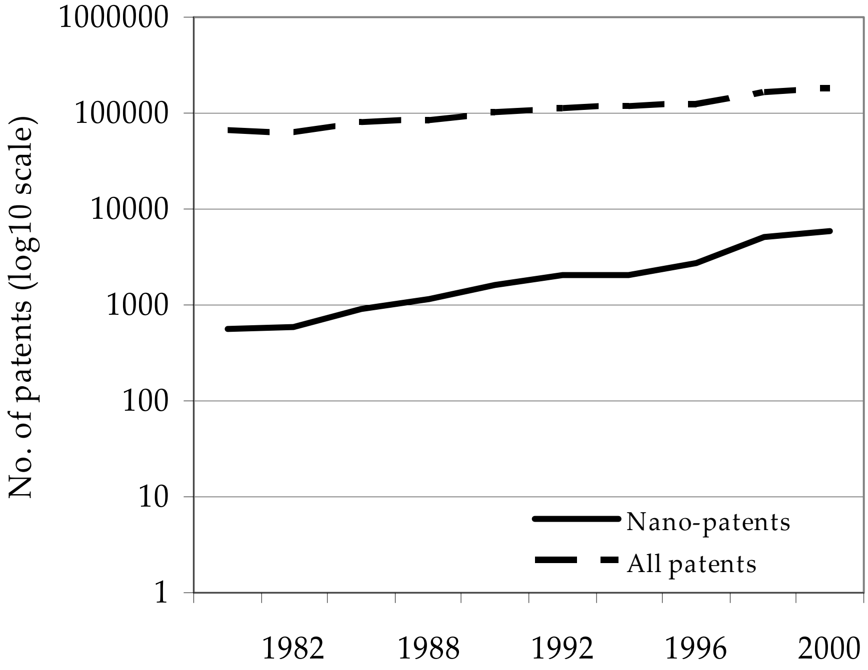

Figure 4. The growth in worldwide nanotechnology patenting and all other patents at the USPTO 1976-2003 (granted patents)

Source: Huang et al. (2004)

These developments and observations get further confirmation in recent analyses of patenting in Europe. Heinze (2004) also finds accelerating growth in patenting after 1997, while the dominance of US assignees again is very clear with 43% of all patents. Similar to developments at the US patent office, Germany scores second with 16% of all European patents, followed by Japan with 9%, France with 6% and the UK with 4%. When country developments are normalized for the different size of economies Sweden, Switzerland and Israel stand out (see also Noyons et al., (2003)). In so far as patenting is a good indicator for the scope for improvement of a technology, it thus seems that nanotechnology is in the process of achieving this first criterion for a GPT although developments clearly hence far are concentrated to the US as the most significant countries also in terms of the size of its R&D system.

The second criterion of *widening uses* throughout various industries, as the technology develops, also provides a strong case for nanotechnology to evolve into a GPT. Nanotechnology foremost represents a new process technology relating to the scale of the processing of materials. As such it can be used throughout most manufacturing industries as the discussion in the previous section of this paper suggests. Nanotechnology is also increasingly incorporating modern biotechnology as it also extends to nanoscale engineering of organic materials (Grodal and Thoma, 2006). Nonetheless, the diffusion of nanotechnology will depend on the compatibility of the broader economic and institutional environment of industries where regional and national, as well as sectoral, specificities will matter greatly. Comparative analysis of nanotechnology is still scant, but a study by Meyer (2000a) points especially to the significance of variations in industrial structures, content and tradition of innovation policy, as well as the composition of scientific networks and communities of practice across countries.

Some additional insights on the widening uses of nanotechnology can be gained from patent analysis in so far as the designation of nanotechnology patents to specific technology fields by patent offices point to industries where they might find application. This aspect is also covered in Huang et al. (2004) for patenting in the US, revealing a clear broadening of the application fields. The fastest growth occurs in various subfields of chemistry, biotechnology and drug development, and electronics components such as semi-conductors, transistors and solid-state diodes. In the European studies Meyer (2000a), Noyons et al. (2003), and Heinze (2004) detect a similar tendency both in terms of the broadening of application fields and their content.

An interesting point in this context is made by Ratner and Ratner (2003). They argue that nanotechnology, in fact, might face few barriers to consumer adoption, at least when hurdles related to regulatory issues and standardization are overlooked. Nanotechnology will be embedded in many existing products, such as computers and pharmaceuticals. As a consequence demand growth will not be curtailed by new product adoption processes, even though e.g. product designers and doctors will have new learning curves to engage in on the supply side. This contrasts with the Internet – as a core ICT technology – where consumers had to learn new aspects of computers to engage e.g. in e-commerce. On the other hand, Ratner and Ratner (2003) also highlight the problem of potentially very long product development cycles due to the nascent and uncertain phase of nanotechnology development.

The popular literature is filled with visions about the multipurpose nature of nanotechnology. The fulfilment of the third criterion of a GPT regarding the broad *range of its usability* will largely depend on when and in which applications and industries 'bottom-up' approaches to nanoscale engineering will emerge as a commercially viable production process. A further barrier for an increasing usability of nanotechnology relates to ethical and safety concerns. Regulations and standards governing the field are relatively non-existent but will surely develop as concern increasingly is raised about e.g. the health hazards of nanoparticles, interoperability of nanoscale devices and system (Rashba et al., 2004). One example of new nanotechnology-related legislation is the forthcoming REACH directive within the EU that relates to the registration and authorization of chemicals.

For further insights a parallel can here be drawn to the multipurpose nature of ICT and modern biotechnology. Freeman (2003) asks why modern biotechnology apparently will not emerge as the GPT of the 21th century while ICT is in the process of doing so. He attributes the relative failure of modern biotechnology to problems of social and political acceptance, lack of appropriate skills, outright opposition in chemicals firms, and above all to the failures to achieve major costs breakthroughs. In contrast, ICT has been among the most widely politically supported technologies as the popularity of such terms as the “information society” and the “knowledge economy” demonstrates. The cost experience of ICT has also been completely different as a series of major technological breakthroughs (semi-conductors, integrated circuits, optical fibres etc.) generated a virtuous circle of cost reduction and expanding sales. Above all, ICT is truly multipurpose as it offers the possibilities of process control in almost every manufacturing and service industry.

According to Freeman (2003) this type of comparison highlights the importance of the historical circumstances during which a GPT emerges and evolves. Further, he highlights the prospects of merging parts modern biotechnology with ICT as a new source of growth, bioinformatics in connection to the health-care sector being one example. Such combinations might also be fruitful in the context of nanotechnology if the range of its uses expands as expected. Some references are already made to combinations of nanotechnology, biotechnology, information technology as well as cognitive science through the acronym "NBIC".

The fourth and final criterion concerning the development *of new complementary technologies and innovations* is difficult to asses in the context nanotechnology since it is still in such a fluid and nascent phase of development. Some insights might again be gained by contrasting the ‘top-down’ approach to nanoscale engineering with the ‘bottom-up’ approach. In particular, it seems that ‘top-down’ approaches already now are partly compatible with lithography, cutting, etching or grinding manufacturing techniques already in use throughout various industries. They thus stand a better chance of generating new complementary technologies and innovations. 'Bottom-up' approaches mark a more radical departure from existing techniques and will thus be less likely to generate complementarities in the near future, especially amongst incumbent firms (Ratner and Ratner, 2003).

New start-ups and university spin-offs might of course also contribute to the generation of complementary technologies and innovations (e.g. components or instrumentation, new organisations and business models) to support the diffusion of nanotechnology. This has perhaps most visible been the case in the ICT industry where various new Internet-based business models are re-emerging after the burst of the dot.com bubble. In the case of nanotechnology it is still difficult to spot such new organisational innovations, or business models, and it is hard to imagine what they might look like. Could, for example, nanotechnology give rise to new service innovations in some form or the other that would pave for rapid diffusion? Again new regulations and standardization might also be a critical to achieve complementarities between nanotechnology and others, as well as between firms and industries that use nanotechnology.

### 3.3. Is nano an exogenous or endogenous technology?

As suggested earlier a GPT might emerge exogenously, while it has to become endogenous to the economic system through technology diffusion in order to have its growth effects. A technology can be considered exogenous if its evolution primarily is driven by non-profit incentives, even though this is quite rare even in the university sector. In contrast, endogenous technologies are driven more explicitly by economic incentives within firms and industries. A key question in much of the literature on the economics of science is how exogenous technologies can be appropriated also economically given their specific nature (for reviews see Stephan (1996) and Audretsch et al. (2002)).

For the sake of clarity it makes sense to distinguish between "nanoscience" and "nanotechnology", a distinction that is sometimes made even though these two domains are highly overlapping in practice. As the definition that we use in this paper suggests nanoscience refers to the understanding of matter at dimensions of roughly 1 to 100 nanometers, while nanotechnology refers to the control and utilization such nanoscale phenomena for specific industrial purposes. To what degree, then, are present developments in the field driven by nanoscience and scientists or nanotechnology and what does this imply for innovation policy? This is obviously a big question without clear-cut answers. However, some insights might again be gained through extant patent and publication analysis. In this context scientific publications can be taken as reasonably proxies for nanoscience developments while patents can function as proxies for nanotechnology developments.

From the discussion in the section above it is already clear that firms are entering the field through the development of patentable nanotechnologies, even though Huang et al. (2004) show that patenting still is concentrated to a few large firms in the ICT, electronics and chemicals industries. Nonetheless, it seems safe to argue that a lions' share of the activity still might be labelled as nanoscience, undertaken by researchers in academia as largely exogenous to the economic system. This can be backed up by the review of Hullmann and Meyer (2003) which shows that the number and growth of publications exceeded, by far, those of patenting in the 1990s. With the exception of enabling inventions related to STM and AFM microscopy in the 1980s, nanoscience thus appears to have driven developments until now. Similar intemporal discrepancies between publications and patenting in the field can be detected in the studies by Zucker and Darby (2003, 2005) as well as Noyons et al. (2003). In cases where firms are involved their innovation activities appear to draw heavily on scientific research at universities as measured by non-patent citations (Meyer 2000; Zucker and Darby 2003; Haung et al. 2004). Apparently these types of patterns are quite general features of new science-based and interdisciplinary fields from the recent past (Grupp, 1996; Llerena and Meyer-Krahmer, 2003)

Questions related to the economic appropriation of exogenous technologies bring us to the issue of technology transfer, a topical issue surrounding the public promotion of nanotechnology in most industrialised countries. The literature on technology transfer is very large and will not be reviewed at any greater depth here. It nonetheless makes sense to highlight a few key insights of this literature as reviewed by Bozeman (2000) in an attempt to identify potential challenges in the context of nanotechnology, the specificities of which have not yet been considered in greater detail (compare with Nicolau (2004, 2006)). Important analytical dimensions in this context concern the organisation subject to technology transfer, the technology transfer media, object, and recipient, as well as the broader economic context.

Regarding the *subjects of technology transfer* Bozeman (2000) suggests that the comparative advantage of the public research organisations is their ability to perform interdisciplinary team research as university departments tend to be organised along stricter disciplinary lines. This might be an observation of relevance also to nanotechnology due to its highly interdisciplinary nature. Nonetheless, universities often can offer a greater array of different *transfer media* to firms in industry due to their educating function also encompassing e.g. collaborative thesis work, outplacement of students and PhDs.

The *transfer object* refers both to the physical technology as well as the related knowledge that firms in industry attempt to receive through the process. As Bozeman (2000) also notes, it is seldom straight-forward to define the object of the transfer as it typically covers both configurations of technical artefacts as well as codified and tacit knowledge. Given the interdisciplinary nature of nanotechnology it goes without saying that the identification of the transfer object might be especially tricky in this context. Further, special attention has been given to the degree to which the technology in question relates to basic rather than applied research as this will affect the readiness of firms to receive the technology and apply it commercially (Cohen and Levinthal, 1990; Henderson and Clark, 1990). This is also a prime concern in the case of nanotechnology where scientific developments still appear to dominate.

The literature has also largely focused on which types of characteristics, capabilities and knowledge bases of firms as the recipient are particularly important for technology transfer. One useful concept here is “technological gatekeepers” to refer to key individuals within R&D systems who play a crucial role in scientific and technological knowledge dissemination (Allen, 1977). Similar to modern biotechnology, Darby and Zucker (2003) suggest that such individuals might be especially important for the transfer of nanotechnology to firms due to ‘natural excludability’ that characterises the field. Natural excludability of a technology arises as cutting edge discoveries initially involves extensive tacit knowledge that is embodied in the discoverers and passed on by “learning by doing” until codification is achieved. Darby and Zucker (2003) use this argument to explain why commercial nanotechnology breakthroughs appear frequently to be transferred to industrial application with the active participation of ‘star scientists’, and suggest that this explains to concentration of nanotechnology patenting to a few firms, regions and countries (see also Meyer et al. (2002); Noyons et al. (2003)).

The *broader economic context* of technology transfer relates to the framework of GPTs and its emphasis on technology diffusion, complementary incremental innovations and facilitating economic and institutional contexts. Bozeman (2000) chooses to highlights the potentials of demand-oriented innovation policies whereby public sectors agencies (e.g. in the health-care sector) can stimulate technology transfer by acting as advanced buyers of new technologies. From the viewpoint of nanotechnology, it seems that the demand environment is still relatively unsettled due to the lack of standards and regulations. In the US, where nanotechnology developments are most rapid, it seems clear that the defence sector also strongly is influencing the direction that this new technology field will take.

### 3.4. Will new entrants or incumbent firms commercialise nano?

The effectiveness of technology transfer might be assessed in various quite different dimensions, although market impact and economic development criteria in practice are the most common ones. Both of these criteria essentially concern the profitability or expansion of firms as the recipients of transferred technology, leading to economic growth in the aggregate at the level of the whole economy. As such they very much concern industrial dynamics, or the relatively role that small and large firms might have as carriers of new technologies. Industrial dynamics is a recurring theme in the economics of technological change. Extant research has sought to find relationships between different types of technological change and industrial dynamics, going all the way back Schumpeter (1911, 1942). Among others Tushman and Anderson (1986), Anderson and Tushman (1990), Rosenbloom and Christensen (1994), Bower and Christensen (1995), Christensen (1997), and Adner and Zemsky (2003) have elaborated further on these relationships.

The basic message of these contributions is that new firms are the ones who tend to introduce emerging technologies to the markets, especially in cases when the technology is discontinuous and destructive with respect to the capabilities and knowledge base of the established incumbent firms. However, over time, as the technology matures, the incumbent firms will regain their position due to the complementary assets that they possess, and assimilate the new technology through takeovers and eventually shift the loci of competition from innovation to prices. At the level of an industry this is visible in the entry of new firms, followed gradually by consolidation and concentration of activities to a fewer number of large established firms. Nonetheless, various modifications to these models of firm and industrial dynamics have also been proposed.

One relevant modification is by Rothaermel (2001). He suggests that incumbent firms may also be in a better position to adapt to discontinuous technologies via cooperation through strategic alliances with new entrant firms when the incumbents possess complementary assets of more generic nature further downstream, e.g. related to production, marketing and retailing. These types of symbiotic relationships between new entrants and incumbents are typical between pharmaceutical companies and new and small firms related to modern biotechnology (Luukkonen, 2005). New entrants and incumbents might thus not only be competitors in emerging technology fields. They might co-exist over time contrary to what most models of industrial dynamics seem to suggest.

Turning to nanotechnology, what appears to be the relative role of small and large firms in commercialisation, and how is firm and industry dynamics unfolding? Again any assessment is speculative due to fluid and nascent phase of developments. Nonetheless, especially when compared with modern biotechnology it seems that at least present day 'top-down' nanoscale engineering approaches are more likely to enhance rather than destroy the capabilities and knowledge bases of incumbent firms. By this logic, large established firms in end-product industries, such as the chemicals, electronics, forest-based and metals industries should be in a good position to assimilate nanotechnology. On the other hand, as discussed earlier, nanotechnology also contains many discontinuous elements especially related to 'bottom-up' nanoscale engineering approaches which might favour new entrants over large incumbents with fixed investments in traditional manufacturing techniques. Only time will tell whether nanotechnology developments will allude, or mark a break, to traditional models of industrial dynamics.

As sketches of emerging value chains related to nanotechnology might suggest the insights by Rothaermel (2001) on the symbiotic co-existence of new entrants and large incumbents is also a possibility. In particular, new start-ups are emerging as providers of intermediate products at nanoscale to be used as components in end-products in the last segment of such a value chain (compare with figure 3 on page 8). Incumbent firms might also strive to form alliances with such start-ups to avoid early stage risks related to nanotechnology. From a small country perspective, such as Finland, an important question to consider is where in such an emerging value chain viable positions might be built. It is also clear that international alliances will be an important aspect of the development and commercialisation of nanotechnology in Finland, whether by large or smaller firms.

# 4. FINNISH NANOTECHNOLOGY POLICY, RESEARCH AND FIRM COMMUNITIES

## 4.1. Comparative R&D volumes and policy initiatives

When the point of departure is taken in the estimated public nanotechnology R&D investments produced by the National Science Foundation in the US (see Figure 1 on page 2) we can see that the investments of the EU as a whole is roughly on par with those of the US and Japan. Nonetheless, within the EU there are significant variations. This is illustrated in figure 5 below based on estimates from various countries both in absolute and relative terms on a per capita basis in the year 2003 (the figure also includes some other big countries for further comparison). It should also be borne in mind that the estimates are subject to uncertainty due to differences in how nanotechnology is defined in various countries.

By a comparison of the absolute levels of public nanotechnology investments we can detect a concentration to the largest countries within the EU, namely to Germany, and France followed by the UK. Of the smaller countries Italy and Holland are on top while Ireland, Sweden, Belgium and Finland invest approximately similar amounts. However, in relative terms, on a per-capita basis, the picture changes quite significantly. From this, more reasonable, viewpoint especially the position of Japan, and the smaller countries Ireland, Switzerland, Holland and Israel stand-out. Further, the position of Finland also strengthens and is elevated above the other Nordic countries Sweden, Denmark and Norway. Accordingly, Finland is a very small player in absolute terms but does invest quite heavily on a per-capita basis. Partly this might be a logical outcome of the general dedication of the Finnish government to R&D, as nanotechnology-related R&D is undertaken in a number of different industries.

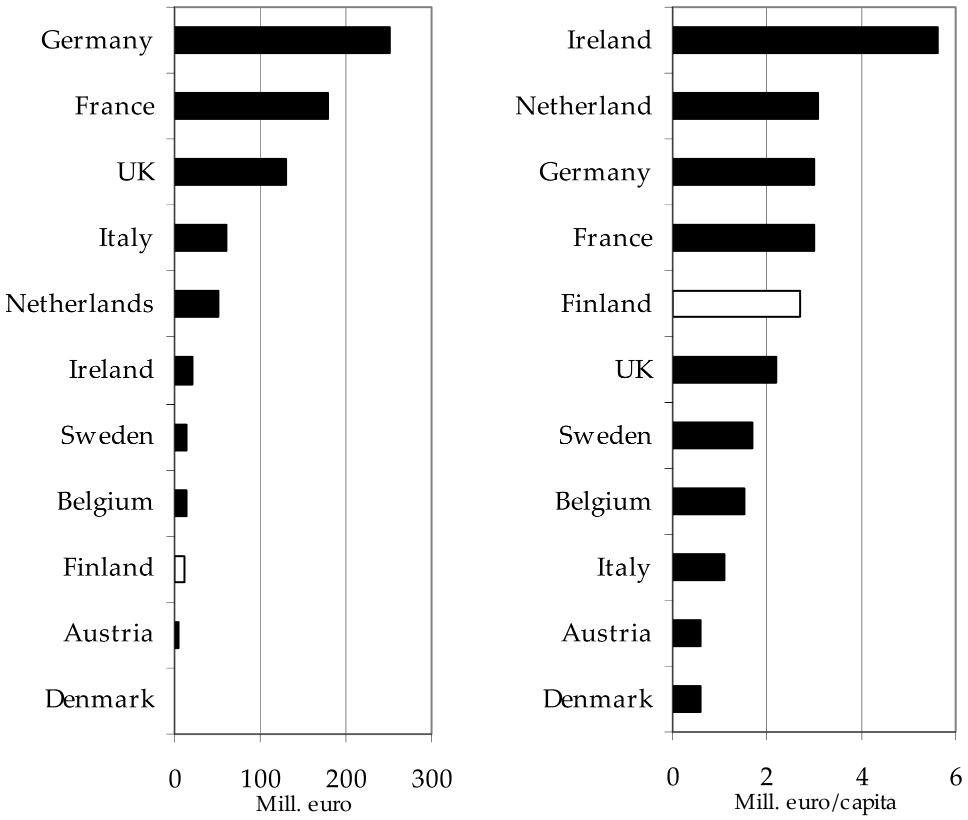

Figure 5. Estimated public nanotechnology R&D investments across countries in 2003

Source: EU (2004)

Previously public R&D investments in nanotechnology have been embedded in science and technology (S&T) programs with linkages to what has subsequently become labelled as nanotechnology (see Appendix 1). However, since the year 2005 these investments have mainly been directed towards dedicated nanotechnology programs commissioned by the Finnish Funding Agency for Technology and Innovation (Tekes) and the Finnish Academy of Science through the launch of the so-called FinNano-programs. These two public R&D funders commissioned an earlier nanotechnology program 1997-1999, albeit volume-wise much smaller. This earlier program focused on nanobiology, self-assembly, functional nanoparticles, nanoelectronics and biomaterials. The FinNano-programs will considerable increase public R&D investments into nanotechnology as Figure 6 below illustrates.

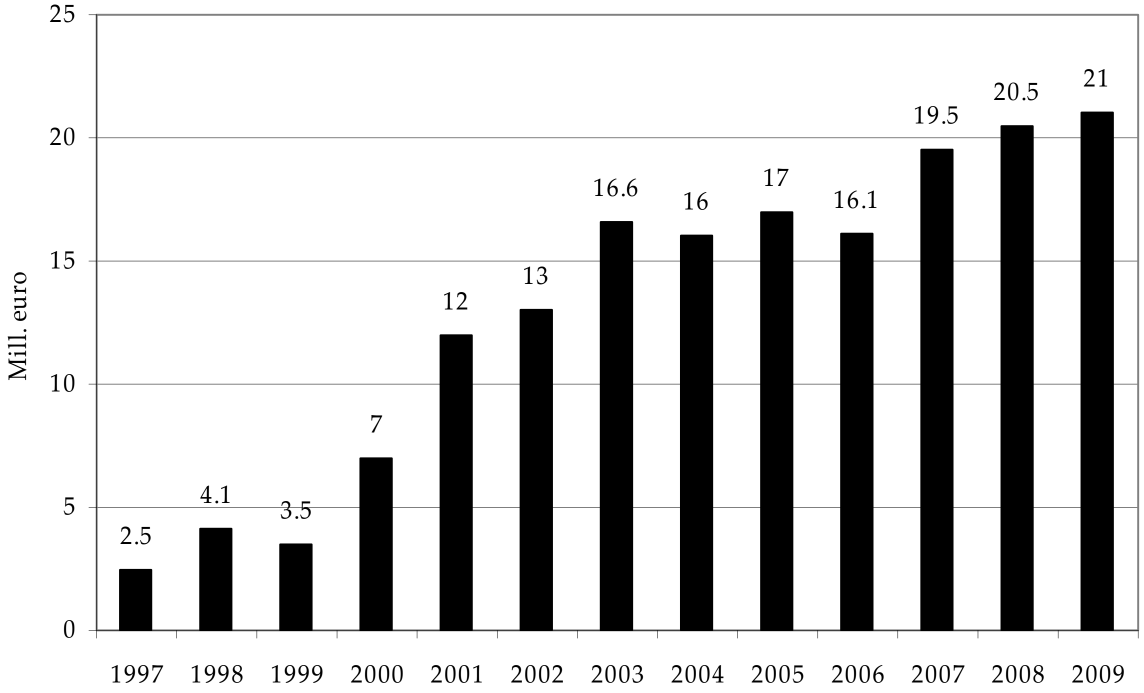

Figure 6. Estimated public nanotechnology R&D investment in Finland 1997-2009

Source: Ministry of Education (2005)

Although there might be overlaps, the division of labor between these two programs derives from the different orientation of the Academy of Finland and Tekes within the Finnish system of innovation. The Academy of Finland focuses on the promotion of nanosciences. Tekes, on the other hand, aims to support the commercialization and general development of nanotechnology by combining nanoscale engineering in chemistry, physics and biosciences. Further, Tekes requires that firms which participate in the program also engage in collaboration with university groups or research organizations (Ministry of Education, 2005).

The program commissioned by Tekes aims to invest 45 million euros in nanotechnology during 2005-2009. Of this, 25 million is intended to cover research at universities or research organizations while 20 million is intended for firm R&D. The focus areas of the program are innovative nanostructure materials, nanosensors and –actuators, and new nanoelectronics solutions. Currently the program covers 20 individual firm projects as well as 15 collaborative projects involving also universities and the Technical Research Center of Finland (VTT). The whole program involves some 75 firms of different sizes. The explicit goal of the program is to both strengthen existing research, but also build new interdisciplinary research groups. It seeks to facilitate technology transfer from the university sector to industry, and speed up the commercialization of nanotechnology. More generally, it also aims to support networking, research mobility and participation in EU nanotechnology related programs.

The program initiated by the Academy of Finland starts in 2006 and is intended to end in 2010. The program will add another 9 million euros to public nanotechnology investments in Finland. It focuses on directed nanoscale self-assembly and functionality, as well as on properties of single nanoscale objects. In the preliminary call for proposals the program has attracted 81 research proposals with 270 individual researchers. The explicit aims of this program are to support basic nanoscientific research, facilitate interdisciplinary approaches, to develop the research environment and training in nanosciences as well as to promote mobility networking, international visibility and utilization of research results both in Finland and internationally.

Both the Academy of Finland and Tekes state that their respective FinNano-programs will be carried out in close cooperation. This includes joint planning and other activities, such as seminars and communications. These programs have been only recently launched, so we will start to see more concrete results within a few years and this will provide additional information about the direction of publicly funded nanotechnology in Finland.

## 4.2. Research communities

The major research and firm communities active in the field are documented in the publications by the Ministry of Education (2005) and the HelsinkiNano-project (2005). The dispersion of the communities in Finland is illustrated in Figure 7 to provide a snapshot of the regional concentration of related knowledge bases, R&D and commercialisation activities.

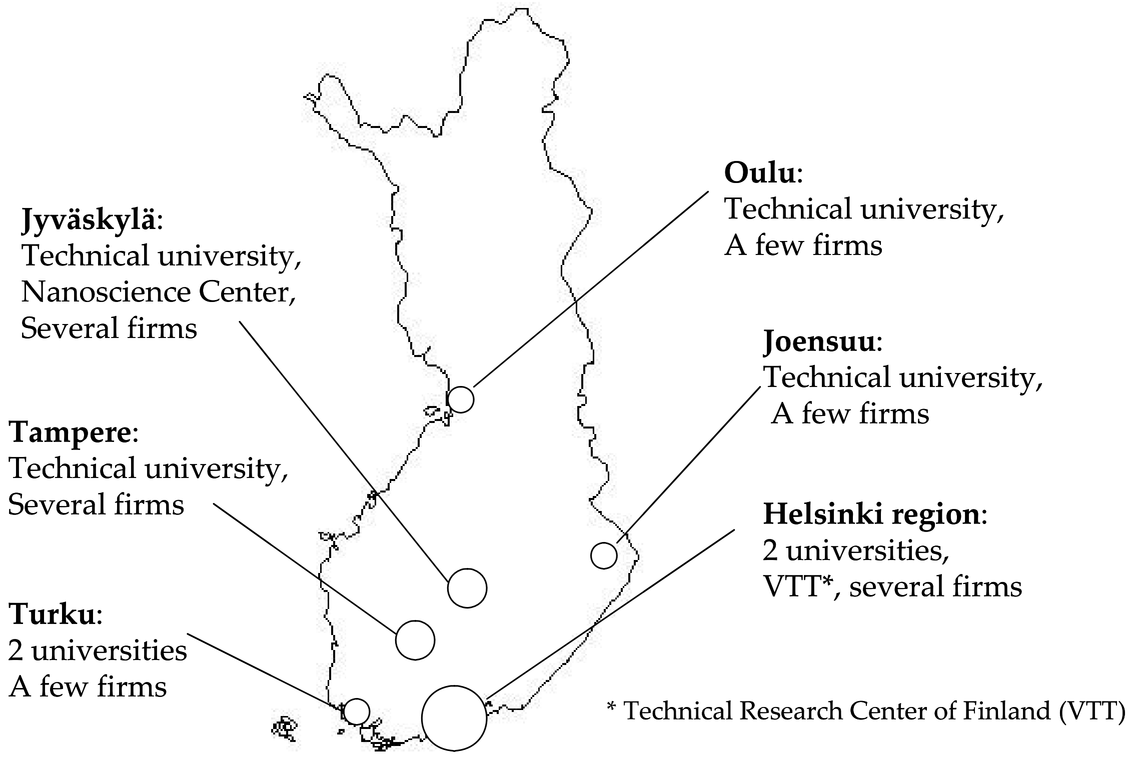

Figure 7. Finnish activities in nanotechnology at the regional level

Source: Ministry of Education (2005), HelsinkiNano (2005)

The nanotechnology research communities are typically closely associated with the technical universities. Hence, they are mainly found in the Helsinki and surrounding areas as the biggest concentration, followed by Tampere, Jyväskylä, Oulu, Turku and Joensuu with smaller concentrations. They also have differentiating focuses, ranging from self assembling materials, quantum electronics, thin layer processes, mesoscopic fermion systems, surface science, physics, virology, to aerosol research. In the following we will briefly characterize these regions and infrastructures, while turning to the related firm communities in the next section.

In Helsinki and the surrounding areas the research focus is on nanoelectronics and nanofotonics, thin layer research and atomic layer deposition techniques (ALD), integrated bio-nano-systems, nanoparticles and nanotubes, theoretical and calculatory research. The three most important actors in the Helsinki region include the University of Helsinki, the Helsinki University of Technology and the VTT. Combined these universities and research organisations host around 30 laboratories and research groups, and altogether consisting of some 200 individual researchers, some of which are associated with the Center for New Materials. These research communities account for roughly 50 percentage of the public funding for nanotechnology (HelsinkiNano, 2005).

In Jyväskylä activities focus on molecular level building of systems and instruments (bottom-up), interaction between molecular level systems and environment, and research of individual molecules and nanostructures. The University of Jyväskylä has established a research centre – the Nano Science Center (NSC) – with around 100 researchers that focuses on basic research and also provides facilities for firms. The Tampere region hosts a large technical with research groups involved in optoelectronics, photochemistry, aerosol research and material processing. Examples of these areas include: quantum dot structures, solar batteries, and thin layer research (MBE). The infrastructure includes the Optoeletronics Research Center (ORC), which is related to the university and a unit of VTT focusing on material processing.

The Turku region has a history of accumulated competencies, research and firm activity in pharmaceuticals and biotechnology and most of the nanotechnology research communities appear to blend in with extant biotechnology research, e.g. biomaterial and diagnostics (compare with Hermans and Kulvik (2006)). The research infrastructure consists of two multi-department universities. In the Oulu region the University of Oulu and a unit of the VTT are focusing on the integration of nanostructures into products, especially in field of printed optics and electronics. The University of Joensuu focuses on optics and photonics, especially in diffraction grating of high efficiency and organic photocells.

### 4.3. Firm communities

Darby and Zucker (2003) suggest that nanotechnology-related entrepreneurship and firms activities center around 'star-scientists' due to 'natural excludability' that characterizes the field (see the discussion in section 3.3. above). By a first approximation the regional dispersion and focus of the different research and firms communities appears to indicate that nanotechnology developments in Finland share some similarities with these insights. In particular, firm activity in nanotechnology seems to concentrate in regions where the research base is strong and the focus of university groups match that of their business focus. Nonetheless, by and large, firm activity in nanotechnology in Finland is still fairly limited Ministry of Education (2005)). In the following we list some of companies that are primarily involved with nanotechnology.

The Helsinki region is also most visible in terms of firm communities with the number of dedicated nanotechnology being around a dozen, altogether employing about 300 persons. In addition, there are over 20 companies in which nanotechnology will play a key role in near future. Examples of firms include Heptagon, Liekki, OptoGaN, ABR Innova and Lumilaser. In the Jyväskylä region dedicated nanotechnology firms include Nanolabsystems and Magnasense. The Tampere region also hosts several firms that are active in nanotechnology. These include Coherent Finland, Modulight, Corelase, EpiCrystals, RefleKron, Cavitar, Oseir and Dekati. In the Joensuu and Oulu there appears to be lesser firm activity. Scant examples include Nanocomp (Joensuu) and Braggone (Oulu).

Many of the above mentioned firms are small, and have often emerged as university spin-offs. In addition to these dedicated nanotechnology firms it is estimated that around 50-60 firms, mostly larger in size, are presently involved directly or indirectly in collaborative nanotechnology R&D projects. This list includes such leading firms as Nokia, the pulp and paper conglomerates UPM-Kymmene and M-Real, as well as a number of medium sized firms with a growing interest in nanotechnology. It nonetheless appears to be clear that the large majority of Finnish incumbents in existing industries still await further nanotechnology developments prior to larger scale commitments. The involvement of these firms will probably be a crucial element of the successful application and commercialization of nanotechnology in Finland.

# 5. FINNISH DEVELOPMENTS VIEWED THROUGH PUBLICATIONS AND PATENTS

## 5.1. Defining nanotechnology publications and patents

Nanotechnology patents and publications have typically been defined through the use of keyword search algorithms dedicated either to their titles, keywords, abstracts or complete texts. There is some variation in the design and precision of such algorithms, ranging from the use of 'nano*' as an all-encompassing search term to various elaborations where 'nano*' is combined with other keywords to narrow down the search. Fraunhofer Institute for Systems and Innovation Research (FhG-ISI) in Germany has developed an algorithm that has been used frequently in this context. The development of this algorithm is based on expert panels, whereby various professionals in the field of nanotechnology in Germany were asked to list and select keywords to describe nanotechnology. The algorithm has evolved into the de facto standard in this context (see Noyons et al. (2003) for a detailed discussion).

To date the development of nanotechnology in Finland has only briefly been analysed in a previous study using a relatively rudimentary search algorithm (VTT Tietopalvelu 2004, 2005). Apart from the definition of nanotechnology, country studies also have to define the nationality of publications and patents. In the case of publications, this is usually done through the nationality of the author. In the case of patents, this is more complex as there is a choice of using information on the country of the priority application, the affiliation of inventors or the patent assignee. Further, patents might be applied and granted at various patent offices around the world whereby appropriate data source concerns also should be taken into account.

In (VTT Tietopalvelu 2004, 2005) the nationality definition was based on the country of the priority patent application, and the focus was on Finnish applied and granted patents globally (i.e. individual patent families usually covering one invention). In the ensuing analysis the focus is likewise on patent families, while the definition of the nationality is extended to also cover inventors with a Finnish affiliation, as well as Finnish assignees. The definition of nanotechnology is also elaborated upon by employing the search algorithm developed by FhG-ISI, and this algorithm is also used to identify publications (see Appendix 2 for the algorithm used). The ensuing analysis thus both deepens extant studies on Finnish developments, and includes new data due to the elaboration of the definitions of nationality and nanotechnology relevancy of the patents and publications.

## 5.2. A comparative perspective on publication and patenting activities

Altogether the search algorithm and nationality criterion identified 2259 Finnish publications and 118 inventions (patent families) that belong to nanotechnology, all of which have been published prior to April 2006.[2] When patent families are broken down into individual patent applications and grant to specific countries we find 295 applications and 114 grants (see Ap-

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[2] The data was provided by VTT Information Services. The patent data is extracted from the Derwent World Patent Index-database. The publications are extracted from the Scisearch-database containing a broad selection of peer reviewed science and technology journals.

pendix 3). This distribution also reflects some aspects of market developments in the sense that patents usually are sought in countries where competitors are judged as particularly strong.

Looking first at the distribution of the grants, the largest share is found in the US followed by Finland as the home country as well as Germany. Outside Europe Australia, Japan and South Korea stand out. In terms of applications – representing the most updated information - the US is in the lead followed by European countries, and Finland in particular as the home country and often the first instance for applications at the European Patent Office (EPO). Outside Europe the share of applications filed in Australia is particularly noteworthy. On closer inspection the grants and applications filed in Australia apparently relate to so-called atomic layer deposition techniques (ALD) discussed further in section 5.3.

As Figure 8 shows the development of Finnish nanotechnology publications and inventions over time appears to follow world-wide trends. Significant publication activity commenced several years prior to patenting even though a couple of inventions appear already in the 1970s as an illustration of the fact that the concept nanotechnology largely also redefines research agendas that have existed for a long time. With reference to the discussion in section 3.3 Finnish nano thus also seems to primarily be driven by nanoscience and scientists, largely exogenous to the economic system.

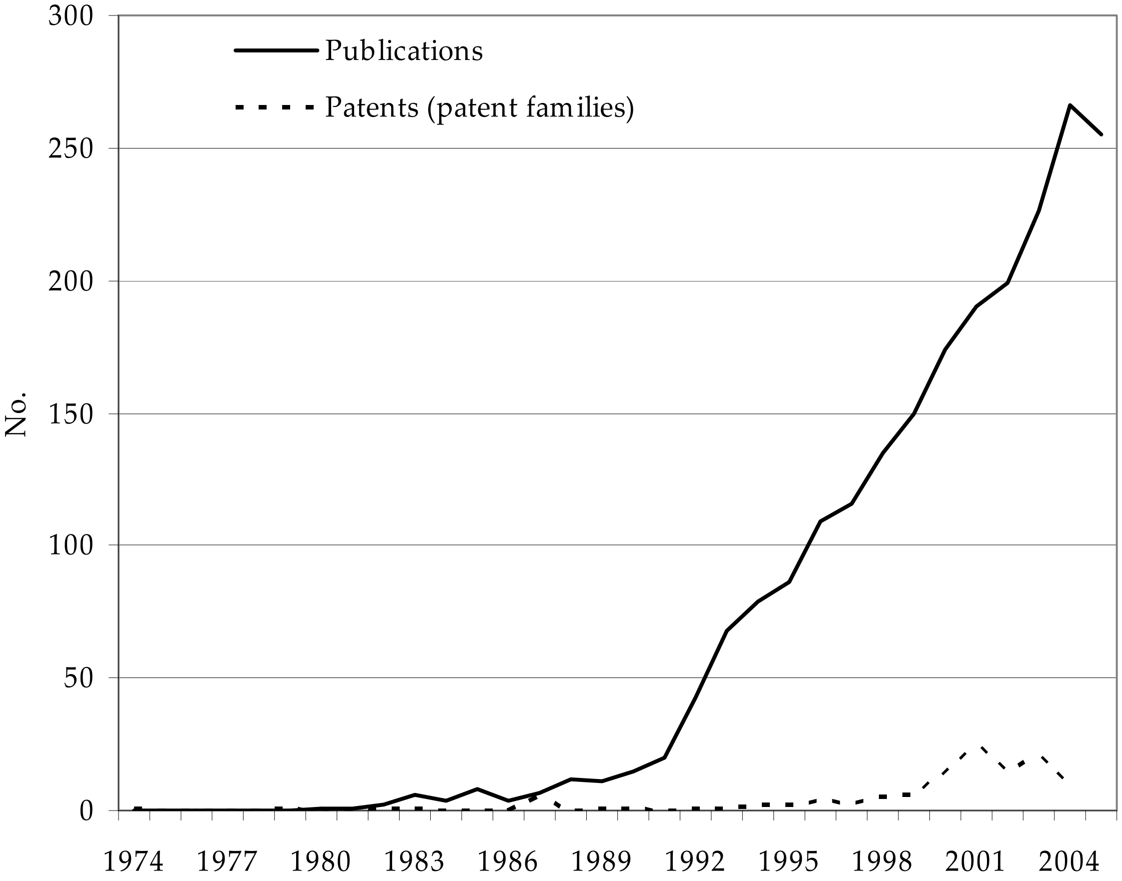

Figure 8. The development of Finnish nanotechnology publications and inventions

These numbers of Finnish nanotechnology publications and inventions can be given further interpretations from an international comparison. From the estimated public nanotechnology investments we know that the volume of Finnish investments on a per capita basis is roughly similar to those in Switzerland, Holland, Germany (and France), while being somewhat higher when compared with Sweden and Denmark. In the following comparison we thus include these countries. Further, the US as the global leader, as well as South Korea and Taiwan are also interesting countries for the sake of comparison. The comparison, both in absolute and relative per capita terms, is illustrated in Figure 9, again using the same search algorithm and nationality criteria.

| | Absolute numbers | | Per capita (thousands) | |
|---|---|---|---|---|
| | Publications | Inventions (patent families) | Publications | Inventions (patent families) |
| US | 83907 | 13609 | 0.29 | 0.05 |
| Germany | 32136 | 3846 | 0.39 | 0.05 |
| Korea | 9722 | 2550 | 0.2 | 0.05 |
| Switzerland | 6477 | 627 | 0.88 | 0.08 |
| Holland | 5282 | 493 | 0.32 | 0.03 |
| Sweden | 4300 | 287 | 0.48 | 0.03 |
| Finland | 2925 | 118 | 0.56 | 0.02 |
| Denmark | 2046 | 115 | 0.38 | 0.02 |

Figure 9. The number of nanotechnology publications and inventions across countries

By a comparison of the absolute numbers of nanotechnology publications and patent families Finland appears in the same league as Denmark while the bigger Nordic and other European countries produce significantly more. Again the dominance of the US and, Germany in Europe, is quite clear. From the more reasonable viewpoint of per-capita adjusted numbers the country size effect vanishes and the position of Finland again strengthens along with the other smaller countries, especially in terms of nanotechnology publications. Of the smaller countries Switzerland stands out, followed by Finland. In terms of patenting the numbers are still so small and do not really differentiate between countries. The overall picture that emerges is thus that Finland appears to dedicate a relatively large share of public R&D investments to R&D and that this is above all visible in a relatively noteworthy volume of nanotechnology publications. Patenting is also picking up but remains on a very low both in absolute and relative terms, similar to most other countries.

### 5.3. Inventors, firms and emerging application fields

Patenting represent an important means to appropriate new technologies, especially in the context of technology transfer from the university or public research sector to industry. Information on the assignees of patents can therefore point to emerging industrial dynamics of a new technology field in terms of the role that independent inventors, small and large firms might have as carriers of new technologies (compare to section 3.4 in this paper). As also suggested previously, patents can indicate towards which application areas and industries the use of a technology is widening as judged by the technology classes to which they are assigned.

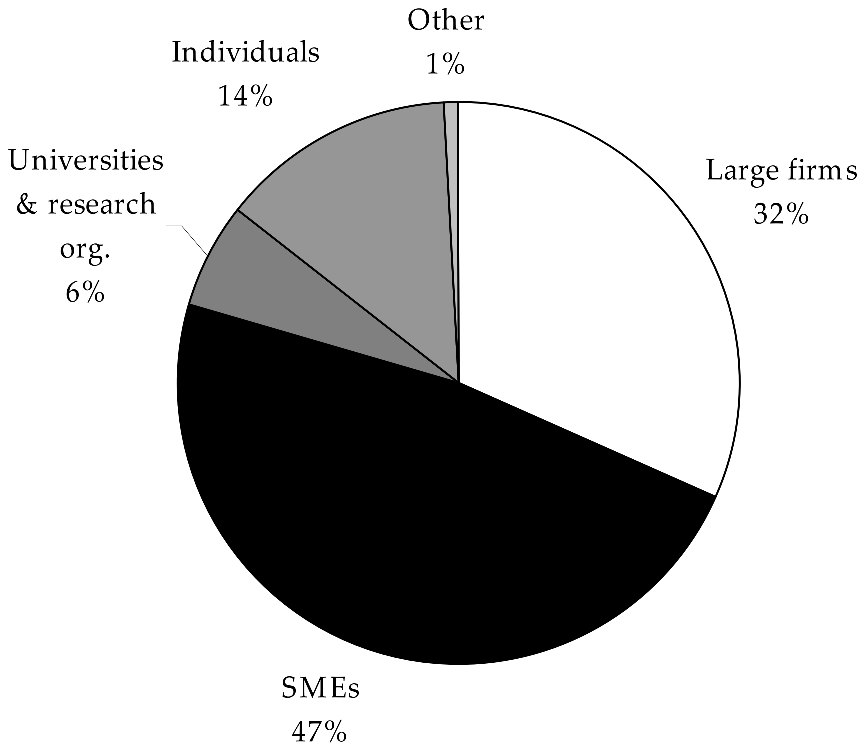

Figure 10. Distribution of inventions (patent families) by type of assignee

Of the pool of 117 assignees, the biggest group consists of SMEs (47%) followed by larger firms with over 250 employees (32%). This is in line with what we know about firm communities in nanotechnology, and it suggests that smaller firms and new entrants presently are important carriers of commercially oriented nanotechnology in Finland (compare to the discussion in sections 3.4 and 4.3). The remaining share is accounted by universities, research organisations and independent inventors although a further analysis of the patent data probably will reveal that a large number of these independent inventors are connected to universities in one way or the other.

Despite the low absolute level of Finnish patenting in nanotechnology until now our data enables some analysis of emerging applications fields. The patent families are assigned to a number of main and secondary technology classes under the International Patent Classification System (IPC) at the time of application. These technology classes indicate the technological fields on which the patented invention is intended to have a bearing in terms of industrial applications. For the sake of clarity, IPC-classes are usually aggregated to higher levels of technology fields. We do this across all main and secondary IPC-classes at two levels of aggregation in the figures below based on the data on Finnish patenting in nanotechnology with reference to the technology field classification in Mancusi (2003) as a commonly used one (Figure 11).

Figure 11 suggests that most nanotechnology applications and commercialisation avenues in Finland presently relate to the broader field of process engineering. The sub-field of surfaces, thermal processes and especially materials processing stand out. The large number of patent families assigned to materials processing reflects R&D activities related to Atomic Layer Deposition techniques (ALD) and their commercialisation in the Helsinki region, and this activity appears to be the commercial spearhead of Finnish nanotechnology at present. However, the assignee of these patent is a US firm with a small R&D unit in Finland even though the origins of ALD traces back to a spin-off ventures from prominent Finnish firms in the chemicals and electronics industries in the 1970s and 1980.

Following process engineering, chemicals and pharmaceuticals appear as the second most important application field of Finnish nanotechnology and this is where the increase in the number of assigned IPC classes has been the most rapid. On a closer look, at the sub-field level, we note the increasing importance especially of organic chemistry, pharmaceuticals biotechnology. This indicates that there is some cross-pollination between nanotechnology and modern biotechnology also in Finland (compare with Grodal and Thoma (2006)). Nano- and biotechnology linkages foremost reflect emerging research and firm communities in the field of modern biotechnology in the Turku region. Beyond this the importance of electrical engineering should also be noted. This is almost solely due to the relevancy of semiconductors as an application field, although it seems that most of these applications also relate to the case of ALD.

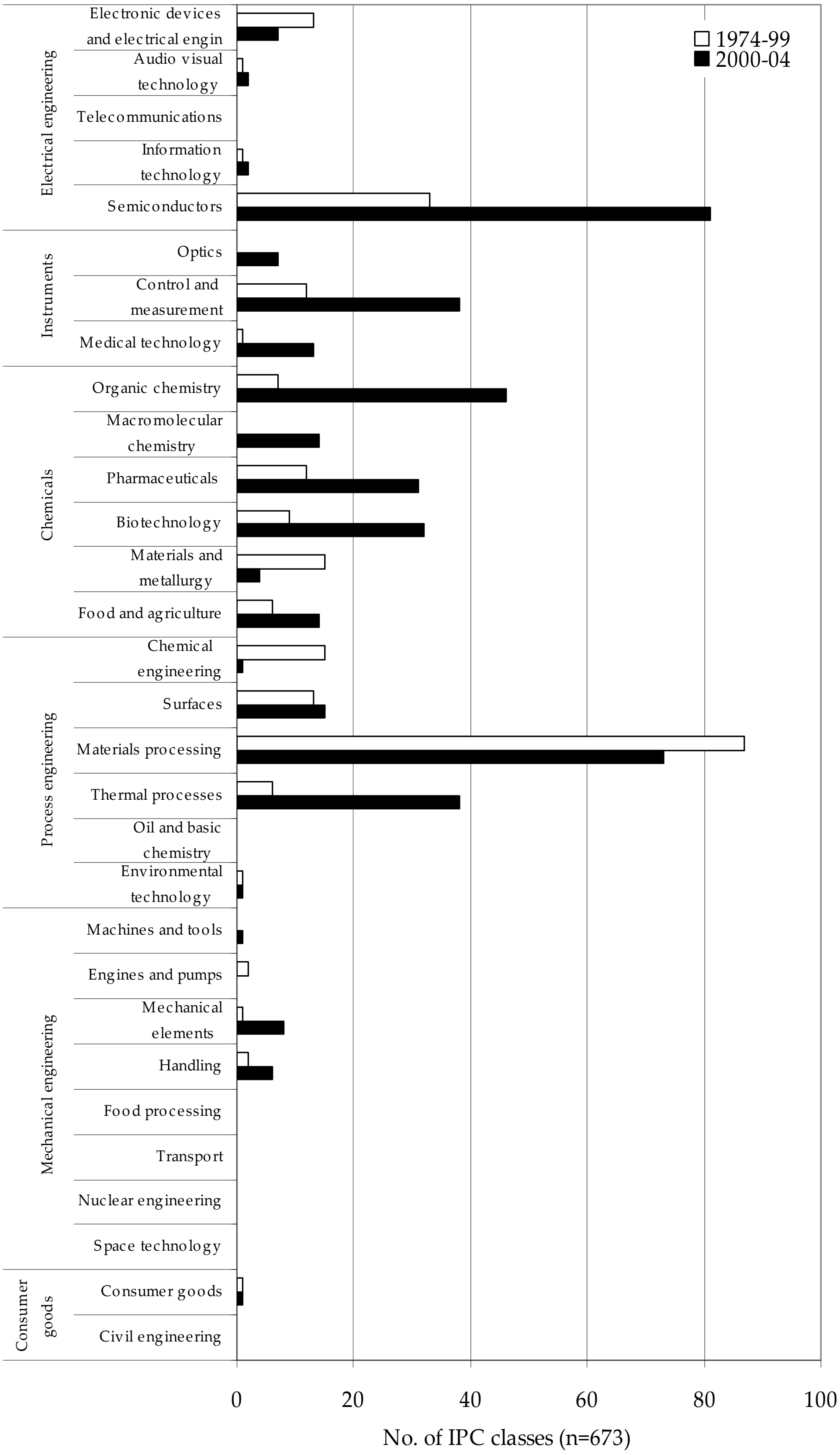

Figure 11. Application fields of Finnish nanotechnology inventions (patent families) 1974-2004

Somewhat surprisingly, the strong Finnish specialisation in ICT does not appear to stand out in this data as the sub-fields of telecommunications and information technology are practically absent. Semiconductor applications have received some references, especially in the 1990s, but the field of electrical engineering as a whole appears to be declining in importance over time. This might be due to the lack of a significant ICT component industry in Finland.

# 6. A SYNTHESISING DISCUSSION

## 6.1. General insights

This paper takes the starting point in the recent very rapid and large public R&D investments into nanotechnology worldwide. Nanotechnology is an umbrella term commonly used to refer to R&D at the 1 to 100 nanometer scale where unique phenomena enable novel applications. The interest given to nanotechnology is largely due to the perceived, and partly also over-hyped, generic nature of this field. There are strong beliefs that nanotechnology holds the potentials to renew existing manufacturing processes, products, services and industries in a revolutionary way. Nanotechnology is often referred to as a new 'general purpose technology' (GPT) which can become the next engine of growth in the world economy.

Smaller countries, such as Finland, are also investing heavily into nanotechnology even though the field is still in a very fluid and nascent phase of development and lacking clear indication of application fields, commercialisation avenues, industrial dynamics and organisation. Accordingly there is a need to shed more light on nanotechnology also from the viewpoint of the economics of technological change to support innovation policy and firm strategies. This paper aimed to conceptualize nanotechnology in this literature, review the limited but burgeoning empirical research towards this end, to provide a brief overview and new insights into the development and emerging application fields, commercialisation avenues of nanotechnology in Finland. It should thus be read as a runner-up to more analytical papers taking an in-depth focus on the Finnish knowledge base, development and commercialisation of nanotechnology.

Conceptually the literature on GPTs – with its Scumpeterian and evolutionary economics connotations – appears useful in this context even though it is far from clear that nanotechnology will evolve into one itself, especially in its present form. The concept is clarifying by highlighting some main features of nanotechnology especially when compared with modern biotechnology and ICT. Nanotechnology is indeed characterised by significant scope for improvement along economically relevant dimensions of merit as the first necessary, albeit not sufficient, criterion of a GPT. This is indicated by the acceleration of nanotechnology-related patenting. Moreover, a few larger countries dominate patenting and thus appear as the technological leaders. Thus, nanotechnology appears to follow a similar development path as modern biotechnology has taken before.

The criterion of the widening use of a GPT over time also appears to fit. Nanotechnology is significantly more generic and could be more application oriented than modern biotechnology. As such it might best be compared to ICT. However, it is clear that the concept 'nanotechnology' also largely redefines previous research agendas in the fields of physics and chemistry, as well as biotechnology, and is thus analytically quite ambiguous. The present core of nanotechnology is the ability to manipulate molecules so that every atom can be put in its most efficient place to achieve a particular functionality. Nanotechnology is thus essentially a new production method with multipurpose functions. Nonetheless, the degree to which the criterion of multipurpose usage will be fulfilled largely depends on when and where such 'bottom up' nanoscale engineering techniques become available on an industrially viable scale. A comparison with ICT and modern biotechnology suggests that many technological, structural and institutional hurdles still lie ahead. The greatest potentials of nanotechnology probably lie in crossovers to existing technologies, firms and industries. These crossovers also have the greatest potentials to generate technologies and innovations which are complementary to nanotechnology.

GPTs might emerge exogenously to the economic system but they have to become endogenous in order to have their longer-term growth effects. In the light of developments over time of nanotechnology-related publications (as rough proxies for scientific developments) and patenting (as rough proxies for technological developments), it seems that nanotechnology still largely incubates in the university sector as "nanoscience", largely exogenous to the economic system. Further, in cases where firms are involved their innovation activities largely appear to draw heavily on scientific research at universities. Accordingly, a topical issue is how nanoscience can be transferred to more widespread use in industry and to what degree the specificities of nanotechnology offers new challenges in this context? These specificities foremost seem to relate to the interdisciplinary nature of the field, to the actual identification of the object of technology transfer both in terms of artefacts and different types of knowledge, as well as to uncertain and longish product development times. The interdisciplinary nature of nanotechnology also suggests that technological gatekeepers, as well as the involvement of scientists in firm activity, is important.

In addition to issues related to technology transfer, an important question is whether large incumbent firms or small new entrants will be the main carriers of commercially viable nanotechnology. Traditional models of industrial dynamics and organisation highlight the role of new entrants in the emerging phases of a new technology, although elaborations of this basic framework also are to be found. As nanotechnology largely also redefines previous R&D agendas and, especially in its 'top-down' approach to nanoscale engineering, also has complementarities with existing manufacturing methods, there are viable reasons to believe that it is more likely to enhance rather than destroy knowledge bases of incumbent firms. In practice a symbiotic co-existence of new dedicated nanotechnology entrant firms and established incumbents is also quite likely as new niche markets in such fields as intermediate nanoscale components and nanotools are emerging. Nonetheless, if and when 'bottom-up' approaches to nanoscale engineering become industrially viable in the unforeseeable future they might also have a quite destructive impact on established incumbent firms and countries.

## 6.2. The case of Finland

Naturally Finnish public R&D investments into nanotechnology only account for a miniscule share of global investments. In a European comparison these investments are at similar absolute levels as in the other small countries Ireland, Sweden and Belgium even though Finland appears to stand-out amongst this reference group on a per-capita basis. Partly this might be due to the general high dedication given to R&D which also spills over to nanotechnology due to the interdisciplinary nature of this field. However, Finland has also recently initiated two dedicated nanotechnology programs with relatively large volumes, implying a noteworthy boost in public R&D investments. Nanotechnology has also been supported before albeit under other labels as a part of biotechnology and materials R&D.

At present research and firms communities are entering, or emerging, in nanotechnology-related fields in close vicinity to the main universities in Finland. Accordingly, there seems to be a certain degree of regional clustering of activities and the role of scientist in firm activities, as well as university spin-offs, appears to be important. Nonetheless, the community of dedicated nanotechnology firms is still small and a relatively large number of these are extant biotechnology firms due to cross-pollination between nanotechnology and modern biotechnology. The biggest concentration of research and firm activity is found in the Helsinki region where the Helsinki University and the Helsinki University of Technology play an important role, along with the Technical Research Centre of Finland (VTT). Some 50-60 larger firms are also showing variable interest in nanotechnology but these incumbents largely still await further developments prior to larger scale commitments.

In the paper publication and patent (patent families) data was used to analyse publication and patenting activities of Finnish nanotechnology-related researchers, inventors and firms, to identify emerging industrial dynamics and organisation, as well as application areas. This data was identified through an elaborate search algorithm based on nanotechnology keywords, and the total figures were compared to those of some other relevant countries to gain perspective. In this comparison the position of Finland in terms of public R&D investments also appears to be reflected further downstream, especially in the number of publications. The level of Finnish nanotechnology publication activity is similar to that of some significantly bigger countries on a per-capita basis. These smaller countries also appear to perform relatively well when compared with the US and Germany.

On closer inspection it is clear that publication activity on a noteworthy scale started much earlier than patenting, and that also Finnish nanotechnology primarily is driven by scientific developments. By a breakdown of different types of assignees SMEs appear as the most important carriers of nanotechnology in Finland at present, although a large share of the related inventions are assigned to a US affiliate. The roots of this US affiliate nonetheless extend back to the 1970s and 1980s to previous Finnish materials research. In terms of application fields Finnish nanotechnology patents foremost appear to have a bearing in the fields of process engineering and chemicals. Individual application sub-fields that stand out within these broader fields include semiconductors, materials processing, pharmaceuticals and biotechnology, with a noteworthy growth especially in the latter sub-fields. Perhaps somewhat surprisingly the sub-fields of telecommunications and information technology are not really visible even though Finland is highly specialised in ICT.

By and large the analysis of nanotechnology publications and patents is in line with what the descriptive account of existing and emerging research and firm communities suggests. Given the competitive position that Finland has in many of the more traditional forest-related, engineering, metals and ICT industries, a key issue of importance to the potentials that nanotechnology might have to renew industries and promote growth in Finland is the degree to which incumbent firms also will take an interest at an early phase. Apart from approaching the commercialization of nanotechnology from this viewpoint, follow-up studies will also focus on the specificities of this field from the viewpoint of technology transfer. A comparative approach is also important, where nanotechnology developments are compared both to the early phases of ICT and modern biotechnology in Finland, as well as to those in other small countries.

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## APPENDIX 1

Earlier or ongoing public programs with linkages to nanotechnology

*Finnish Funding Agency for Technology and Innovation (Tekes)*

- FinNano (2005-2009)
- NeoBio, New biotechnology (2001–2005): modern biotechnology methods
- COMBIO, Healthcare biomaterials (2003–2007): Tissue technology materials andmethods, new materials and implants for drug delivery
- ELMO, Miniaturization of electronics (2002–2005): micro/nano-hybrids, modules for nanoelectronics and –optics, biomaterial components macromolecules based on macromolecules and self assembly
- FinnWell, Healthcare technology program (2004–2008): diagnostics
- PINTA, Self cleaning surfaces (2002–2006): research and application of physical, chemical and electronical properties on surfaces
- FINE, Particles - Technology, Environment and Health Technology Program (2002–2005)
- Lääke2000
- Diagnostiikka2000

*Academy of Finland*

- FinNano (2006-2010)
- TULE, Future electronics (2003-2006)
- EMMA, Materials and Microsystems for electronics (1999-2002)
- MATRA, Material and structure research (1994-2000)
- NEURO, Neuroscience
- MICMAN, Microbes and humankind

## APPENDIX 2

Keyword search algorithm used to identify Finnish nanotechnology publications and patents (based on work done at FhG-ISI)

```
SEA ABB=ON  PLU=ON  (((NANOMETER# OR NANOMETRE# OR NM OR
SUBMICRO?) AND (CHIP# OR ELECTRON? OR ENGINEERING OR DIAMETER
OR SIZE# OR LAYER# OR SCALE OR ORDER OR RANGE OR DIMENSIONAL))/
TI NOT (WAVELENGTH# OR ROUGHNESS OR ABSORB?)/TI)
SEA ABB=ON  PLU=ON  (((NANOMETER# OR NANOMETRE# OR NM OR
SUBMICRO?)(A)(CHIP# OR ELECTRON? OR ENGINEERING OR DIAMETER OR
SIZE# OR LAYER OR SMALL? OR SCALE OR ORDER OR RANGE OR
DIMENSIONAL)) NOT (WAVELENGTH# OR ROUGHNESS OR ABSORB?))
SEA ABB=ON  PLU=ON  (((NANOMETER# OR NANOMETRE# OR NM OR
SUBMICRO?)(2W)(CHIP# OR ELECTRON? OR ENGINEERING OR DIAMETER
OR SIZE# OR LAYER# OR SMALL? OR SCALE OR ORDER OR RANGE OR
DIMENSIONAL)) NOT (WAVELENGTH# OR ROUGHNESS OR ABSORB?))
SEA ABB=ON  PLU=ON  (NANOPARTICL? OR NANO(W)PARTICL?) NOT
(ABSORB? OR INK OR POLISH?)
SEA ABB=ON  PLU=ON  (NANOANALY? OR NANOBAR? OR NANOBOT# OR
NANOCAGE# OR NANOCHANNEL? OR NANOCERAMIC OR NANOCHANNEL# OR
NANOCHIP# OR NANOCIRCUITRY OR NANOCLUSTER# OR NANOCOATING# OR
NANOCOLL? OR NANOCOMPUT? OR NANOCOMPOS? OR NANOCONDUCT? OR
NANOCRY OR NANOCRYSTAL? OR NANODEVICE# OR NANODES)
SEA ABB=ON  PLU=ON  (NANODIMENSIONAL OR NANODISPERS? OR
NANODOMAIN# OR NANODROP? OR NANOENGIN? OR NANOELECTR? OR
NANOFABRIC? OR NANOFEATURE# OR NANOARRAY? OR NANOBIO? OR
NANOREACT? OR NANOCATAL? OR NANOPHOTO? OR NANOHOL? OR NANOPIT#
OR NANOPILLAR#)
SEA ABB=ON  PLU=ON  (NANOGAP# OR NANOGEL OR NANOGLASS? OR
NANOGRAIN? OR NANOGRANULAR OR NANOGRID? OR NANOIMPRINT? OR
NANOINDENTATIO OR NANOINSTRUCTIONS OR NANOILLUMINATION)
SEA ABB=ON  PLU=ON  (NANOLAYER? OR NANOLITHO? OR NANOMACHIN?
OR NANOMANIPULATOR# OR NANOMAGNET? OR NANOMATERIAL?)
SEA ABB=ON  PLU=ON  (NANOMECHANICAL OR NANOMEMBRANE OR
NANOMETRIC? OR NANOMICR? OR NANOMOTOR# OR NANOPEPTID? OR
NANOPHASE# OR NANOPHOTOLITHOGRAPHY OR NANOPIPEL? OR NANOPLOTTER
# OR NANOPOWDER# OR NANOSENSOR# OR NANOSCALE? OR NANOARCHITECTU
R OR NANOPATTERN OR NANOCAVITY)
SEA ABB=ON  PLU=ON  (NANOPOR? OR NANOPRINTING OR NANOPROBES OR
NANOPROCESS? OR NANOPROGRAM? OR NANORIBBONS OR NANOROD# OR
NANOROPE# OR NANOSCIEN? OR NANOSCOP? OR NANOSCRATCHING OR
NANOSEMICONDUCTOR# OR NANOSENS? OR NANOSEQUENCER OR NANOSILIC?
OR NANOSILVER OR NANOSIZ?)
SEA ABB=ON  PLU=ON  (NANOSPHER? OR NANOSPREADING OR NANOSTATS
OR NANOSTEP? OR NANOSTRUCT? OR NANOSUBSTRATE OR NANOSUSPENSION
OR NANOSWITCH? OR NANOSYST? OR NANOTECHNOLOG? OR NANOTEXTUR?
OR NANOTIPS OR NANOTRIBOLOGY OR NANOTROPES OR NANOTUB? OR
NANOWIRE? OR NANOWHISK?)
SEA ABB=ON  PLU=ON  (NANOTOPOGRAPHY OR NANOCHEMISTRY OR
NANOREGOGNITION OR NANODOT OR NANOPUMP# OR NANOCAPS?)
SEA ABB=ON  PLU=ON  SCANNING PROBE MICROSCOP? OR SCANNING
TUNNEL? MICROSCOP? OR SCANNING FORCE MICROSCOP? OR ATOMIC
FORCE MICROSCOP?  OR NEAR FIELD MICROSCOP?
SEA ABB=ON  PLU=ON  FUNCTIONALLY COATED SURFACE# AND NANO?
SEA ABB=ON  PLU=ON  (BIOCHIP OR BIOSENSOR) AND (A61# OR G01N
OR C12Q)/IC
SEA ABB=ON  PLU=ON  DNA(2A)CMOS
SEA ABB=ON  PLU=ON  (BACTERIORHODOPSIN OR BIOPOLYMER# OR
BIOMOLECULE#)AND (G11# OR G02# OR G03# OR G06#)/IC
SEA ABB=ON  PLU=ON  BIOMOLECULAR TEMPLAT? OR VIRUS(2A)ENCAPSULA
TION OR MODIFIED VIRUS
SEA ABB=ON  PLU=ON  NANO? AND IMPLANT?
SEA ABB=ON  PLU=ON  (PATTERN? OR ORGANIZED) AND (BIOCOMPATABILI
TY OR BLOODCOMPATABILITY OR BLOOD COMPATABILITY OR CELL
SEEDING OR CELLSEEDING OR CELL THERAPY OR TISSUE REPAIR OR
EXTRACELLULAR MATRIX OR TISSUE ENGINEERING OR BIOSENSOR# OR
IMMUNOSENSOR# OR BIOCHIP OR CELL ADHESION)
SEA ABB=ON  PLU=ON  MICRO?(2A)NANO?
SEA ABB=ON  PLU=ON  NANO(W)(ARCHITECT? OR CERAMIC OR CLUSTER#
OR COATING# OR COMPOSIT## OR CRYSTAL?)
SEA ABB=ON  PLU=ON  NANO(W)(DEVICE# OR DISPERSE# OR DIMENSIONAL
OR DISPERSION# OR DROP# OR DROPLET OR ENGINEERING OR ENGINEERE
D OR ELECTRODES OR ELECTRONIC#)
SEA ABB=ON  PLU=ON  NANO(W)(FABRICATED OR FABRICATION OR
FILLER# OR GEL OR GRAIN? OR IMPRINT OR IMPRINTED OR LAYER#)
SEA ABB=ON  PLU=ON  NANO(W)(MACHINE# OR MANIPULATOR# OR
MATERIAL# OR MECHANICAL OR MEMBRANE OR METRIC?)
SEA ABB=ON  PLU=ON  NANO(W)(PHASE# OR POWDER# OR PORE# OR
PORO? OR PRINTING OR ROD# OR SCALAR)
```

## APPENDIX 3

The distribution of individual Finnish nanotechnology patent applications and grants across countries as of April 2006.

| | Patent applications | Patent grants |
|---|---|---|
| Austria | 1 | 0 |
| Australia | 53 | 6 |
| Belgium | 1 | 0 |
| Brazil | 9 | 0 |
| Canada | 4 | 1 |
| Switzerland | 1 | 0 |
| China | 1 | 3 |
| Former Czechoslovakia | 2 | 0 |
| Czech Republic | 1 | 0 |
| East Germany | 3 | 0 |
| Germany | 4 | 19 |
| Denmark | 2 | 0 |
| Finland | 43 | 22 |
| France | 5 | 0 |
| UK | 6 | 3 |
| Hungary | 1 | 3 |
| Israel | 2 | 0 |
| Japan | 21 | 5 |
| South Korea | 19 | 6 |
| Mexico | 1 | 0 |
| Holland | 1 | 1 |
| Norway | 4 | 0 |
| New Zealand | 2 | 0 |
| Sweden | 1 | 0 |
| Russia | 2 | 1 |
| Taiwan | 14 | 1 |
| US | 87 | 37 |
| South Africa | 4 | 0 |
| Spain | 0 | 5 |
| India | 0 | 1 |
| Europe | 76 | 53 |
| North America | 91 | 38 |
| Japan | 21 | 5 |
| ROW | 107 | 18 |
| Total | 295 | 114 |
| EPO | 45 | 10 |
| WO | 73 | 0 |

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