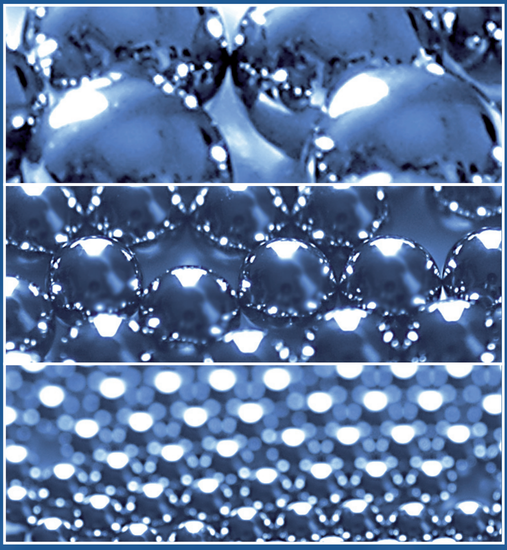
Nanotechnology and industrial renewal in Finland

A synthesis of key findings



Christopher Palmberg – Tuomo Nikulainen

NANOTECHNOLOGY AND INDUSTRIAL RENEWAL IN FINLAND

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Helsinki, 30.4.2008

Christopher Palmberg & Tuomo Nikulainen

Contents

1 The NANOREF project

This is the final synthesis report of the NANOREF (Nanotechnology and Industrial Renewal in Finland) project undertaken by Etlatieto Ltd. The NANOREF project started in February 2006 and ended in October 2007. It was funded by the National Technology Agency of Finland (Tekes) and the Technology Industries of Finland Centennial Foundation.

After the exceptional success of information and communications technologies (ICT) and Nokia in the 1990s, concern has been raised about the sustainability of Finnish industrial renewal and competitiveness. The knowledge- and R&D-oriented strategy that Finland has pursued is coming under increasing competitive pressure due to developments in emerging newly-industrialised economies. Meanwhile, many traditional industries in Finland are seeking new innovation opportunities to renew themselves from within in a more fundamental way. The role of generic and enabling technologies has been especially important in the Finnish context in the past. This is best exemplified through the early application of digital technologies in the 1970s, which paved the way for the success in ICT. The application of ICT-related automation and process technologies has been pivotal for the competitiveness of the pulp & paper industry, and recently high hopes have been placed on the application of modern biotechnology and nanotechnology.

The NANOREF project found inspiration in some of these concerns, the previous success and present challenges that Finland has had in the fields of ICT respectively modern biotechnology. While ICT, modern biotechnology and nanotechnology are different types of technology fields all three of these share certain general purpose characteristics that can imply significant economic effects in terms of productivity and growth (indeed ICT has already proven some of its characteristics in this respect), and thereby represent fields in which countries are eager to build strongholds. The overreaching aim of this project was to provide insights about the present role and future possibilities on nanotechnology to renew established, and create new industries in Finland. The project focused on issues related to the knowledge base of Finnish nanotechnology, technology transfer, establishment of new companies in the field and the links between nanotechnology and existing companies and industries in Finland. The project was primarily designed to support the ongoing FinNano technology programme commissioned by the Finnish Funding Agency for Technology and Innovation (Tekes) during 2005–2010. The project was also designed to further establish the competencies of Etlatieto in the economics of new/emerging technologies.

This report synthesises the key findings of the research and related publications undertaken during the project. The project has produced altogether six working papers (two of which also have been published in the working paper series of foreign institutions) and one forthcoming working paper related to another adjacent project. One of these working papers has been published in an academic peer reviewed journal while two others are being submitted. The project has also produced four other publications for the general public. In addition to the research publications, new databases were collected and several interviews were conducted with representatives from academia, industry and the public sector. Further, the results have been presented at seven conferences and/or workshops both in Finland and abroad.[1] The project will also generate one PhD thesis.

The project was headed by Christopher Palmberg (Etlatieto).[2] The researchers in the project, in addition to Christopher Palmberg, were Tuomo Nikulainen (Etlatieto) and Mika Pajarinen (Etlatieto) who provided invaluable assistance in data collection and analysis. The steering group of the project included Markku Lämsä (Tekes), Eija Ahola (Tekes), Runar Törnqvist (Helsinki University of Technology) and Pekka Ylä-Anttila (Etlatieto).

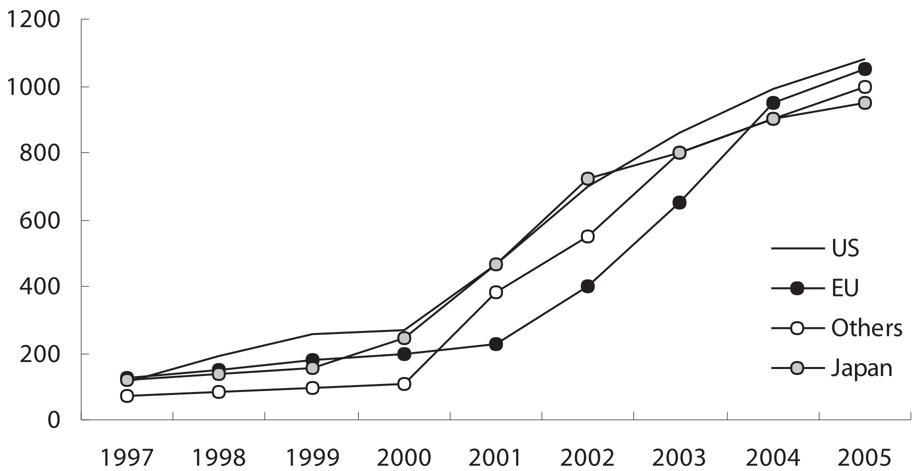
1 All NANOREF publications and presentations are listed under references at the end of this report and are referred to throughout.
2 Before the end of the project Christopher Palmberg took up a position at the OECD in Paris with responsibility over the Working Party on Nanotechnology (WPN).

2 Nanotechnology as the next general purpose technology?

Nanotechnology has recently received much attention amongst science, technology and innovation policies in most highly industrialised and some rapidly developing economies. Nanotechnology is generally considered to promise much from business opportunities for individual companies throughout various industries to broader socio-economic benefits for society at large. These promises have contributed to exponential growth in public R&D funding (Figure 1). Hardly any other technology field has benefited from as much public R&D investments globally in such a short time as nanotechnology, and private sector investments are also picking up and contributing further to the global race for prominence in the field. The payoffs of these investments in terms of expected future global market size have been estimated somewhere in the range of 150 billion USD in 2010 to as much as 2.6 trillion USD in 2014 with some 2 million new jobs predicted (Hullmann, 2006, LuxResearch, 2006).

Whenever a new technology field, such as nanotechnology, emerges there is speculation about its potential effect on longer term economic growth. If a core technology has a substantial and pervasive effect across the whole of society,

Figure 1 Public R&D investments in nanotechnology globally, mill. USD



Source: Roco (2006).

it is often termed a 'General Purpose Technology' (GPT). The dissemination of microelectronics that subsequently opened up the field of ICT in the last quarter of the 20th century bears all the hallmarks of a GPT. Even though most of the above-mentioned forecasts on nanotechnology are bound to be very inflated due to uncertainties in defining nanotechnology products, companies and markets, analysts have nonetheless suggested that nanotechnology might develop into the next general purpose technology and engine of growth for the 21st century, converging with, and following in the footsteps of, ICT (Lipsey et al., 2005, Youtie et al., 2007).

Box 1 Four criteria of a GPT

1) Must have *significant scope for improvement* along with economically relevant dimensions of merit so that its cost of operation will fall over time
2) Has a *widening variety of uses within an industry* as it develops
3) Must have a *wide range of different uses in various industries*
4) Must generate a range of other new *complementary technologies and innovations*

Nanotechnology is essentially an umbrella term to capture a set of sciences and technologies that enable the understanding and control of matter and processes at a very small length scale (typically in the range of 1–100 nanometres). One nanometre is one billionth of a metre; nanotechnology is essentially the engineering of matter even down to the level of individual atoms. At these size scales we move from traditional to quantum physics domains that are still partly less known. Traditional materials yield to new optical, mechanical and reactive properties, thereby enabling new functionalities, as well as the development of completely novel materials, devices and products. Due to these characteristics nanotechnology has the potential to affect virtually every area of economic and productive activity as well as many aspects of daily life.

From available statistics on the number of patents in this emerging field it is clear that nanotechnology is developing very rapidly and towards a broad range of applications in various technology fields and industries, and thereby appears to fulfill at least 2–3 of the first 4 criteria of a GPT. Primary application fields include electronic components and systems, pharmaceuticals and health care, instrumentation, environmental technologies and new materials for a whole range of different applications in many industries. It is noteworthy that some sub-fields of nanotechnology appear to be converging with both ICT and biotechnology. The effects on productivity and economic growth will probably come with a significant delay but the convergence between ICT, nano- and biotechnology might also generate some unexpected economic effects in the near future.

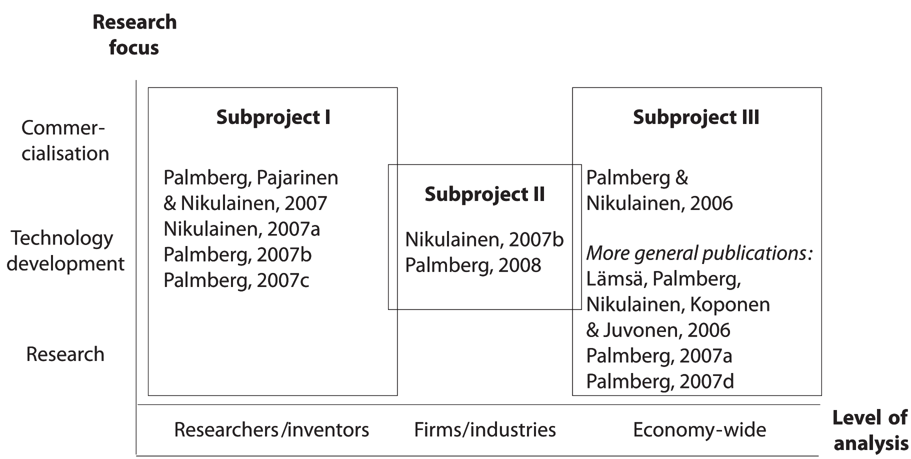
However, with reference to the fourth criteria of a GPT the key issue for unlocking the potential of nanotechnology is whether innovational complementarities will be achieved. These complementarities include not only technologies and innovations that support the further industrial uptake of nanotechnology. They should also comprise balanced policy responses that take into account broader societal issues such as environmental, health, safety and ethical concerns.

3 Project aims, limitations and report structure

In the light of the socio-economic promises and challenges, increases in public R&D investments and broader societal issues it is clear that a small country, such as Finland, should also consider how to best approach and benefit from nanotechnology. Even though the broader societal issues are important the starting point for this project was to assess the developments in Finnish nanotechnology from the perspective of economics and innovation policy (for an extensive discussion of broader societal issues related to nanotechnology, see Roco and Bainbridge (2003) and Roco (2006)).

More precisely, the NANOREF project considered to what extent nanotechnology is aligned with existing companies and industries in Finland, as well as to what degree this technology field is achieving innovation complementarities, and what the main challenges are in this context. The project sought to highlight the nature of the nanotechnology-related knowledge base in Finland, the specificities and challenges of the transfer of nanotechnology from universities to industry, as well as the role that new dedicated versus established companies play in providing commercialisation paths, and finally to consider how nanotechnology links up with Finnish industries and the economy in a broader sense. These focus areas are illustrated in Figure 2 below, complemented with the respective publications to which this report mainly refers.

Figure 2 Focus areas of the NANOREF project and related publications



4 Defining nanotechnology

Before proceeding some additional words on defining nanotechnology are warranted as this is a debated issue (see e.g. Granqvist, 2007). It is often the case with generic technologies, such as nanotechnology, that the definitions and delimitations of what it comprises are disputed. Some claim that nanotechnology represents a relatively coherent set of technologies that together amount to a new knowledge base that challenges, and even disrupts, present scientific and engineering principles. Others suggest that nanotechnology is a hype-word in the sense that it merely redefines existing research agendas, and mostly enhances knowledge bases that scientists and engineers already draw upon. This discussion is ongoing and this report will not dwell any further on it. Instead it makes sense to highlight a pragmatic definition of nanotechnology that is much referred to and useful also in the context of this report.

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. This smallness is also the clue to the scientific, technological and economic significance of nanotechnology. When the size of material approaches the nanoscale they start to gain 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 large number of industries.

As suggested above nanotechnology is characterised by certain novel and unique aspects that underline its relevance as a concept and subject for science, technology and innovation policy, even though its convergent nature and applicability in various technology and industrial areas also has to be taken into account. Even though various agencies have proposed definitions on nanotechnology for developing and collecting indicators and statistics there is no commonly agreed upon international framework for this purpose (see Appendix for a list of policy-related definitions).

While there are different definitions of nanotechnology it is clear that each one of them highlights three fundamental aspects. First, nanotechnology is considered to involve the purposeful "control", "manipulation" or "handling" of matter at a very small length scale. This is intended to eliminate from the definition material and processes that have come about through 'accidental' nanotechnology, that is, nanotechnology that is naturally occurring or that has occurred without purposeful engineering under controlled settings.

Second, there is an emphasis of a particular length scale where research and engineering moves into the nanotechnology domain due to the occurrence of size-dependent phenomena because of the dramatic increases in surface area, or other effects that only emerge at the nanoscale. In the US definition a threshold of 100 nanometres is suggested for the onset of such size-dependent phenomena. The threshold is merely suggested to indicate an approximate point along the continuum when classical rules of physics start to give way to quantum mechanics and the related new, and as of yet less well-known, phenomena that nanotechnology in important ways relies on.

The third common aspect is the insistence that nanoscale research, development and engineering also enables "novel" or "new" industrial applications or "technological innovations" based on new functionalities arising from the size-dependent phenomena. 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 nano-scale 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 so far been the more common while the bottom-up approach still in an early development phase.

Before proceeding to the case of Finland, it should be noted that the definition used in the NANOREF project corresponds to the one introduced by the NNI in the US. By this definition 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, modeling, and manipulating matter at this length scale*". The use of this definition can be motivated by the following three factors. First, this NNI definition is the most common one adhered to globally for innovation policies. Second, it also closely corresponds to the definition used by policymakers in Finland. Third, it appears to be relatively clear-cut, short and concise, and is thereby useful for empirical purposes when approaching researchers, companies and others in the field.

5 Nanotechnology in Finland

Based on:
"Nanotechnology as a general purpose technology of the 21st century? – An overview with focus on Finland"
Palmberg, C. & Nikulainen, T. (2006)
ETLA Discussion Papers no. 1020 / DIME Working Papers, RAL 2.3a, 2006-2

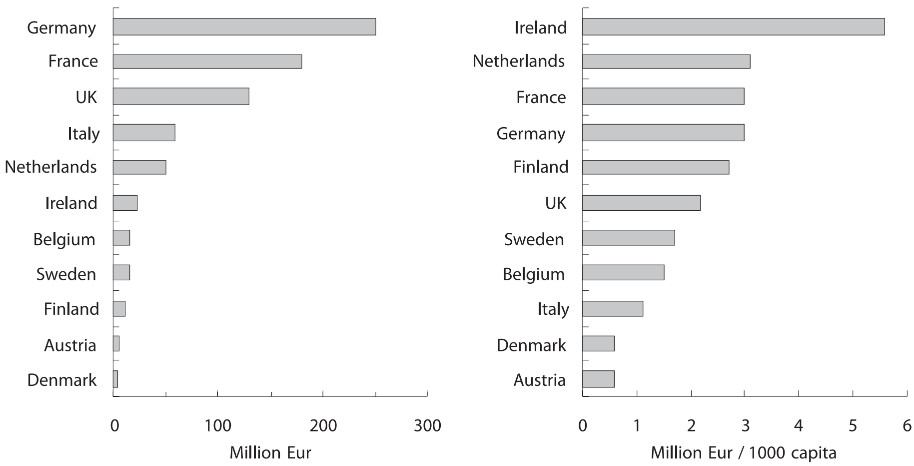
"Nanoteknologiastako seuraava yleiskäyttöinen teknologia? – Havaintoja Suomen näkökulmasta"
Palmberg, C. (2007a)
ETLA Discussion Papers no. 1072

Nanotechnology is a multidisciplinary and science-based field that poses big challenges especially for small countries with limited resources. In Finland nanotechnology is an interesting field due to its 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 and expensive research facilities, instrumentation and the development of new commercialisation avenues.

Nanotechnology differs in many important ways both from ICT and biotechnology. It still in a very fluid and nascent phase of development and it is unclear what are the most viable application areas and commercialisation avenues for this technology. Apart from the hype, consultancy reports 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 where the risks of misguided R&D investments are high.

When looking at the absolute levels of public nanotechnology investments in Europe, we can see that Finland invests approximately similar amounts as many of the other smaller, comparable, countries (Figure 3). However, in relative terms, on a per-capita basis, the picture changes quite significantly. The position of Finland 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. This is also partly a logical outcome of the general dedication of the Finnish government to R&D.

Figure 3 Public nanotechnology R&D investments across countries 2003



Source: EU (2004).

Box 2 The FinNano programmes

Tekes

The Tekes FinNano technology programme (2005–2010) has a volume of approx. 70 million EUR, including 25 million EUR in research funding, and 20 million EUR in corporate financing from Tekes.

The objective of the nanotechnology programme is to:

1. Strengthen research activities
2. Foster technology transfer for public sector to industry
3. Support networking and researcher mobility
4. Encourage enterprises to see the potential of nanotechnology

Academy of Finland

The Academy of Finland FinNano research programme (2006–2010) has a volume of 9.45 million EUR.

The objective of the research programme is to:

1. Support high-level basic research on nanosciences
2. Activate interdisciplinary and transdisciplinary approach in the field
3. Develop research environments and researcher training in the field
4. Support networking, international visibility and exploitation of research results
5. Advance responsible development of nanotechnology

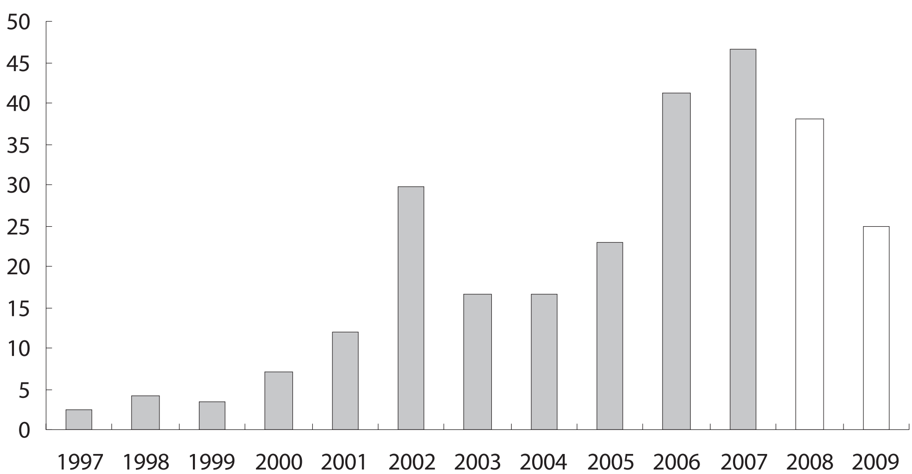
Source: Tekes & Academy of Finland.

There has been variety of public policy involvement in nanotechnology. Since 2005 these investments have mainly been directed towards dedicated nanotechnology programmes commissioned by the Finnish Funding Agency for Technology and Innovation (Tekes) and the Academy of Finland (AKA) through the launch of the FinNano programmes.

Both of the above-mentioned programmes are carried out in close collaboration with Tekes and Academy of Finland. The main difference in the programmes is that the former focuses on applied research and commercialisation of R&D, while the latter funds solely basic research. Due to these programmes the public investments in Finland have increased significantly in recent years as illustrated in Figure 4.

While these two programmes are aimed directly towards nanotechnology and nanosciences, there have been other technology and science programmes that have links to nanotechnology and nanosciences of which some are ongoing. Earlier or ongoing public programmes with linkages to nanotechnology include for Tekes: NeoBio (2001–2005), COMBIO (2003–2007), ELMO (2002–2005), FinnWell (2004–2008), PINTA (2002–2006), FINE, (2002–2005), Lääke2000 and Diagnostiikka2000; and for Academy of Finland: TULE (2003–2006), EMMA (1999–2002), MATRA (1994–2000), NEURO and MICMAN.

Figure 4 Estimated public R&D investment in nanotechnology in Finland, mill. EUR



Note: Last two years are estimates.
Source: Ministry of Education (2005) and Tekes (2008).

After reviewing some of the relevant policy efforts, we move on to the description of activities in nanotechnology and nanosciences in Finland. In this project a key-word based search algorithm was used to identify Finnish nano-related academic publications and inventions (see Palmberg and Nikulainen 2006 Appendix 2 for more details). While there are policy-related definitions as of now no internationally agreed upon definition exists for the identification and development of indicators to trace developments. As a consequence existing research has developed a number of dedicated definitions and indicators for specific purposes, such as these keyword search algorithms for the identification of nanotechnology publications and patents.

The searches identified 2 259 Finnish publications and 118 inventions (patent families) that belong to nanotechnology, all of which were published prior to April 2006. When patent families are broken down into individual patent applications and grant to specific countries 295 applications and 114 granted patents were found.

The development of Finnish nanotechnology publications and inventions over time appears to follow world-wide trends (Figure 5). Significant publication

Box 3 Advantages and disadvantages of patent data

Advantages:

- Patents are closely linked to inventions
- They cover a broad range of technologies on which there are sometimes few other data sources
- The contents of patent documents are a rich source of information
- Patent data are available as long time series and across many (most) countries
- It is readily available from patent offices

Disadvantages:

- The value distribution of patents is skewed as many patents have no industrial application (and hence are of little value to society) whereas a few are of substantial value
- Many inventions are not patented because they are not patentable or inventors may protect their inventions using other means
- The propensity to patent differs across countries, industries and companies
- Differences in patent regulations make it difficult to compare counts across countries
- Changes in patent law over the years make it difficult to analyse trends over time

Source: Based on OECD (2007).

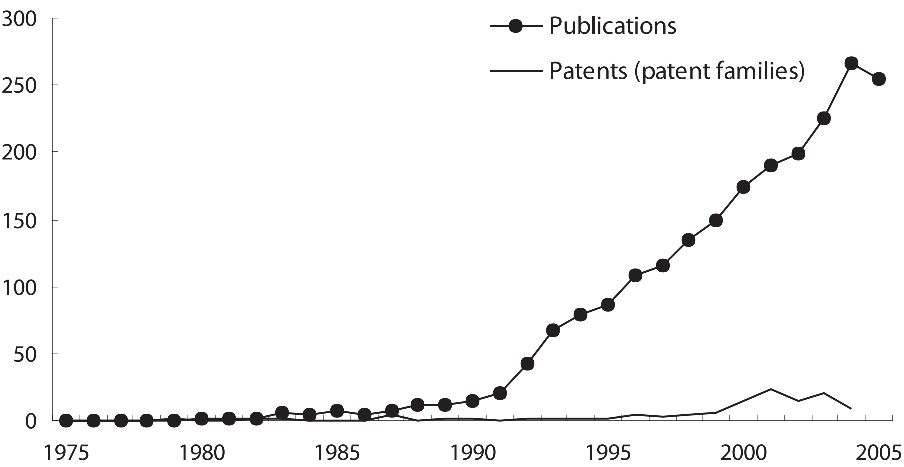
activity commenced several years prior to patenting. Finnish nanotechnology thus also seems to primarily be driven by the nanosciences and scientists.

The overall picture that emerges is that Finland appears to dedicate a relatively large share of public R&D investments to basic research and that this is above all visible in a relatively noteworthy volume of nanotechnology publications. Patenting is also picking up but remains very low both in absolute and relative terms, similar to many other countries (the exceptions being especially the US, Japan and some larger European countries).

At present research and firms communities are 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 scientists in firm activities, as well as university spin-offs, appears to be important. The biggest concentration of research and firm activity is found in the Helsinki region where the University of Helsinki and Helsinki University of Technology play an important role, along with the Technical Research Centre of Finland (VTT). Larger firms are also starting to show variable interest in nanotechnology (see section 7 for a further discussion about company involvement in nanotechnology).

In terms of both primary and secondary application fields Finnish nanotechnology patents foremost have a bearing on the fields of process engineering,

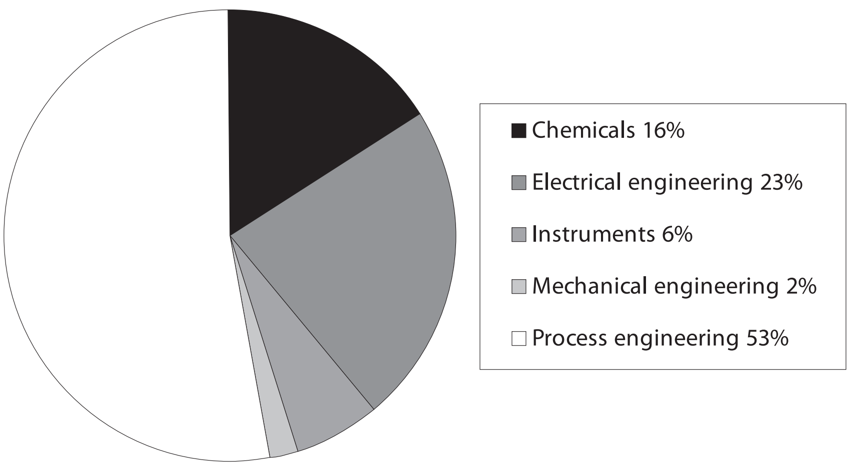
Figure 5 Finnish nanotechnology publications and inventions until present (most recent year available at the time of data extraction)



chemicals and electric engineering. 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, only semiconductors appear as a significant field from this viewpoint.

Given the competitive position that Finland has in many of the more traditional forest-related, engineering, metals and ICT industries, it is important that established companies also take an interest in nanotechnology and identify viable business opportunities to renew their existing products and processes, as well develop new ones. Given the accelerating R&D investments, as well as the relatively strong scientific performance of Finnish researchers in the underlying fields, the transfer of nanotechnology from research to industry is a particularly important issue.

Figure 6 Application fields of Finnish nanotechnology patents (patent families) 1974–2004



Main conclusions of this section

- Measured by R&D expenditures and publications Finland is a minor player globally
- When R&D expenditures and publications are measured relative to the size of the population Finland emerges as a country with significant activity
- Nanotechnology developments in Finland are still very science- and research- oriented while innovation activity amongst companies in industry is limited
- Nonetheless, nanotechnology innovation is relatively evenly distributed across application areas especially in the fields of electrical engineering (semiconductors), chemicals, and process engineering
- Some regional clusters are emerging within Finland with the biggest concentration in the Helsinki area

6 Nanotechnology transfer as a key issue

Based on:
“Transferring science-based technologies to industry – Does nanotechnology make a difference?”
Palmberg, C., Pajarinen, M. & Nikulainen, T. (2007)
ETLA Discussion Papers no. 1064

“What makes a gatekeeper? – Insights from the Finnish nanocommunity”
Nikulainen, T. (2007a)
DRUID Working Paper no. 07–09.

The nanotechnology keyword search algorithm mentioned above was also the starting point for identifying researchers, inventors and to some extent also companies active in the field. Altogether the Finnish nanotechnology publications and patents revealed 1 002 individuals as authors or inventors of which 804 were researchers at universities or research institutes and 173 were inventors at companies. In order to analyse technology transfer these researchers and inventors were approached with a web-based questionnaire. Questions related to the degree of involvement of the individuals in the field of nanotechnology were especially important. These questions allowed for a split of the data whereby the profile and activities of ‘less nanotechnology intensive’ individuals could be compared with the ‘more nanotechnology intensive one’s’ for the purpose of identifying whether nanotechnology really raises new issues during technology transfer. In the first round the analysis was restricted to the viewpoint of researchers at the universities and research institutes.

At the outset it was clear that the keyword search algorithm would identify researchers and inventors with different opinions about their degree of involvement in nanotechnology-related research and/or development (R&D) activities. In fact as many as 52% of all respondents considered themselves involved in nanotechnology by the definition used. The other 48% identified only a slight or no involvement. These figures highlight the definitional ambiguities surrounding nanotechnology and also suggest that Finland presently has a population of some 500 researchers active in this field.

Turning to the background of the researchers some interesting results emerged. The researchers do not differ to any great extent in terms of educational level, professional experience or age. However, those more intensively

Box 4 Survey practicalities

Following the identification of the population of 1,002 researchers and/or inventors in Finland a cumbersome exercise for checking for duplicates and misspelled names was undertaken during February–April 2006, followed by an identification of the contact information using the Internet (email, telephone, address, link to www home page). Each researcher and/or inventor was contacted by email for the Web-based survey during September-November 2006.Particular care was taken to enhance the user-friendliness of the survey as well as to facilitate the inclusion also of researchers and inventors at firms, in practice by branching it according to whether the respondent mainly conducted research or development activities in a university or research institute, or firm setting. The survey yielded an overall response rate of 60%, distributed by the affiliation of respondents as shown in the table below. The response rate can be considered exceptionally good for a Web-based survey.

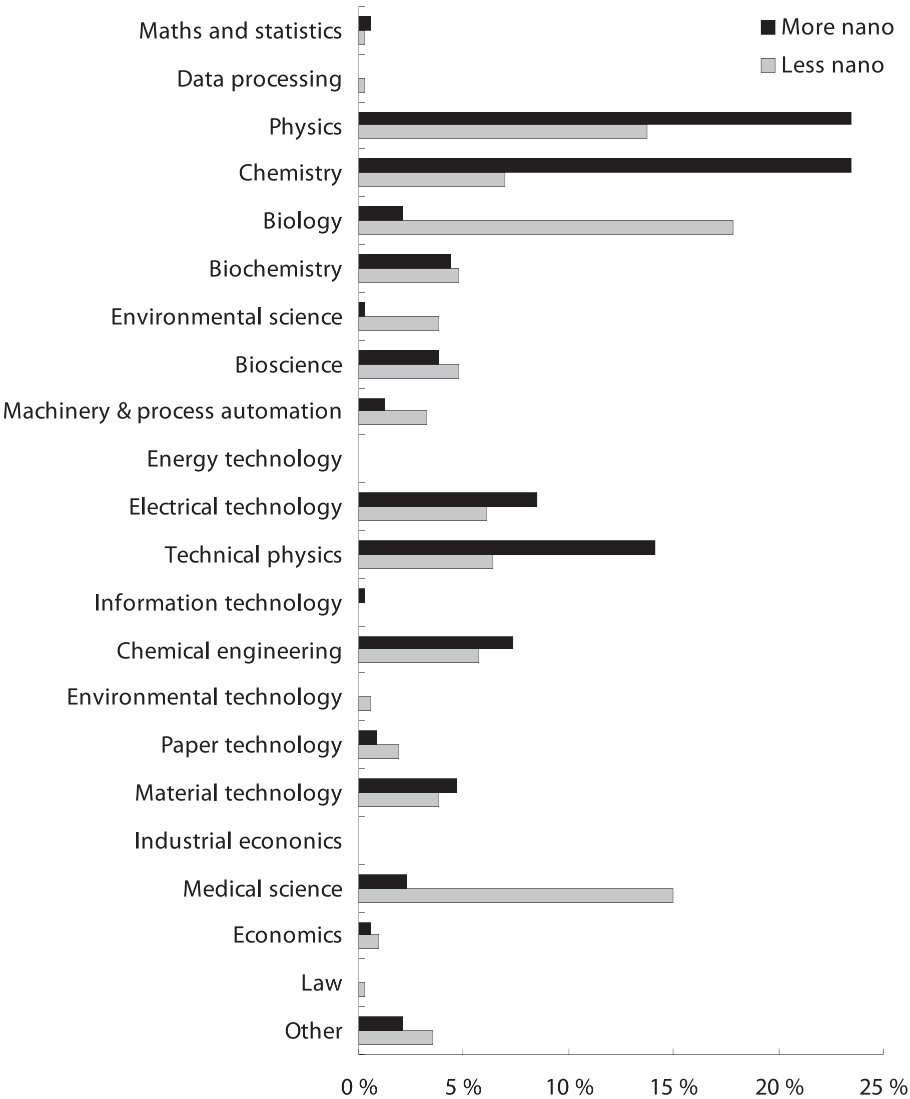
		Universities	Research institutes	Firms	Other	Total
No response	N	195	96	94	14	399
Response	N	397	116	79	11	603
		67 %	55 %	46 %	44 %	60 %
Total	N	592	212	173	25	1002

involved in nanotechnology have a stronger educational background in physics and chemistry. The less involved ones lean relatively more to biology and medical science. This result underlies the cross-pollination between nanotechnology and biology (Figure 7).

In terms of challenges in the interactions with firms the major ones relate to the basic research orientation of their research, to difficulties in identification of commercial applications, to the lack of business or market skills of researchers or the lack of interest by the firm. However, these challenges appear characteristic of all the research fields that we covered through the survey as nanotechnology intensity does not differentiate across the two subsets of respondents. Hence, nanotechnology does not appear to produce new specific challenges on top of those that characterise the transfer of science-based technologies to companies in general.

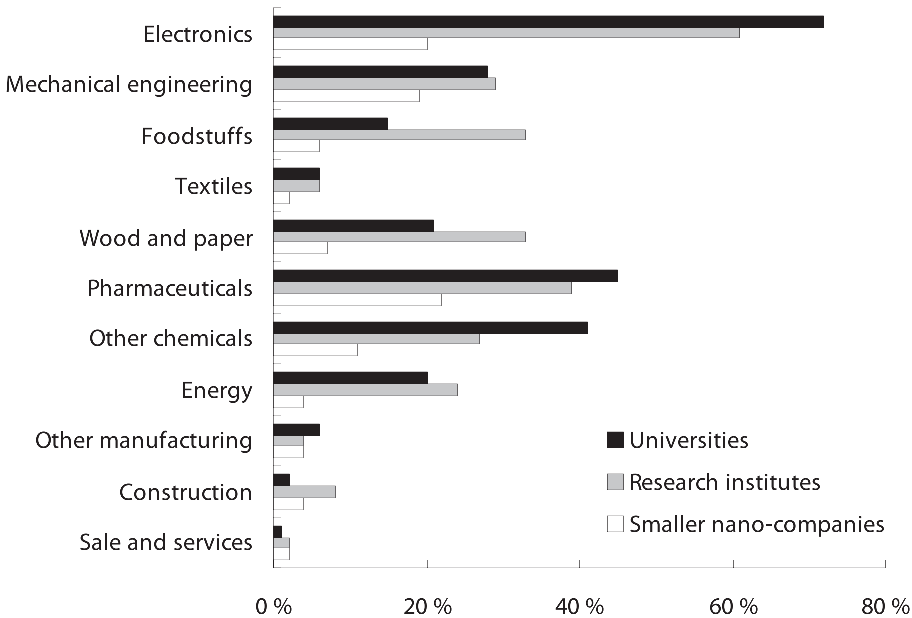
The potentials of technology transfer and the widespread commercial application of nanotechnology are reflected in the broad range of industries that the respondents from the different affiliations highlighted (Figure 8). Nonetheless,

Figure 7 Educational background of survey respondents



the more R&D intensive electronics, mechanical engineering, pharmaceuticals and other chemicals industries stand out amongst those respondents that are more nanotechnology intensive. The high frequency for the electronics industry is probably a natural consequence of Finnish specialisation in ICT. However, it

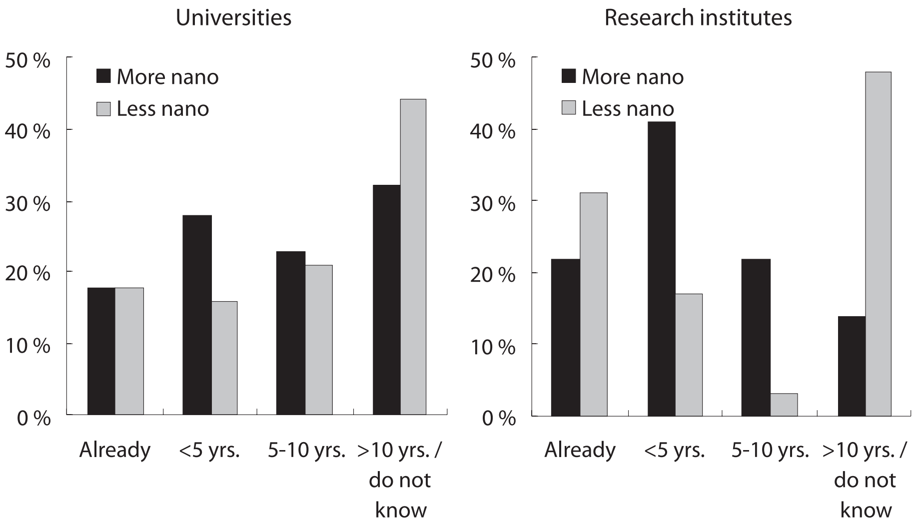
Figure 8 Envisioned application industries by the different affiliation of respondents



is interesting to note that this application field is primarily the envisioned one for researchers at universities and public research institutes while the smaller nanotechnology-dedicated companies appear to have their preoccupation elsewhere. The high frequency for pharmaceuticals is interesting and underlines further the cross-pollination between bio- and nanotechnologies.

In terms of expected durations from research to commercial breakthroughs of their own research higher nanotechnology intensity produced more optimistic judgments amongst the respondents (Figure 9). This seems to be a direct consequence of the fact that commercialisation durations per default are longer for biology-related research, especially when related to biopharmaceuticals, which mainly comprises the comparative less-nanotechnology intensive group in this set-up. These biopharmaceuticals products have to undergo various clinical trials prior to market introduction. Sometimes these researchers might work in research fields not intended for commercialisation in the first place. An interesting result is also that those respondents identifying applications in the more traditional and less R&D-intensive industries of metals and engineering,

Figure 9 Commercialisation durations of own research by affiliations of respondents



foodstuffs, pulp & paper, energy and construction also expected shorter commercialisation durations.

While the analysis presented so far provides insights into technology transfer from the viewpoint of researchers more insights are needed into the factors contributing to the results of this process. Key individuals, or 'gatekeepers', play an important role transmitting knowledge across disciplinary and organisational boundaries, and thereby also facilitate the productive use of the related knowledge in industry. Due to the diverse educational profile of the researchers involved in nanotechnology it would thus be important to identify the role and characteristics of such gatekeepers throughout inter-personal networks involved in technology transfer.

The identification and characterisation of gatekeepers was possibly through linking the researcher survey with further data on the publications and patents in which they have been involved . Further, the survey provides information about the self-reported judgement of researchers of the intensity by which they transfer knowledge to companies. The survey was used to identify and observe aspects related to gatekeepers and technology transfer while the patent and publication data were used to identify social networks based on either co-inventorship or co-authorship, and assess the position of gatekeepers in these networks. Further, regression analysis was used to pinpoint gatekeeper characteristics especially pertinent for technology transfer intensity.

The main determinants for intensive technology transfer by gatekeepers are above average age, commercial motivation for current research and active interaction with companies both informally and formally. All of these characteristics have a positive impact on the intensity of technology transfer, as does the centrality of individuals in these networks as measured by the range of co-inventor and -authorship. Interestingly the educational background or work experiences does not have a significant impact. Thus the role of gatekeepers is indeed also significant for technology transfer throughout social networks of nanotechnology, even though a descriptive analysis of these networks indicates that such networks still are fragmented in Finland with low level of connectivity between research groups.

The main conclusions from this section

- There are roughly 500 researchers working in core nanotechnology fields in Finland, mainly with an educational background in physics and chemistry
- Researchers with a background in biology-related sciences also contribute to nanotechnology-related research
- From the viewpoint of public sector researchers nanotechnology transfer to industry does not appear to introduce new specific challenges
- The main challenges relate to the basic research orientation of their activities, difficulty identifying commercial applications for research, insufficient knowledge of business, and firms' lack of interest
- The largest share of researchers envision commercial applications in the electronics, pharmaceuticals and chemicals industries
- Expected commercialisation durations (from idea to market) appear shorter in the more traditional industries of metals and engineering, foodstuffs, pulp & paper, energy and construction
- Certain individuals (gatekeepers) are especially important in technology transfer; most notable those with commercial motivations and an ability for interdisciplinary collaboration
- Research networks appear to be fragmented

7 Commercialisation routes: new versus established companies

Based on:
"The transfer and commercialisation of nanotechnology – A comparative analysis of university and company researchers"
Palmberg, C. (2007b)
ETLA Discussion Papers no. 1086 / Journal of Technology Transfer

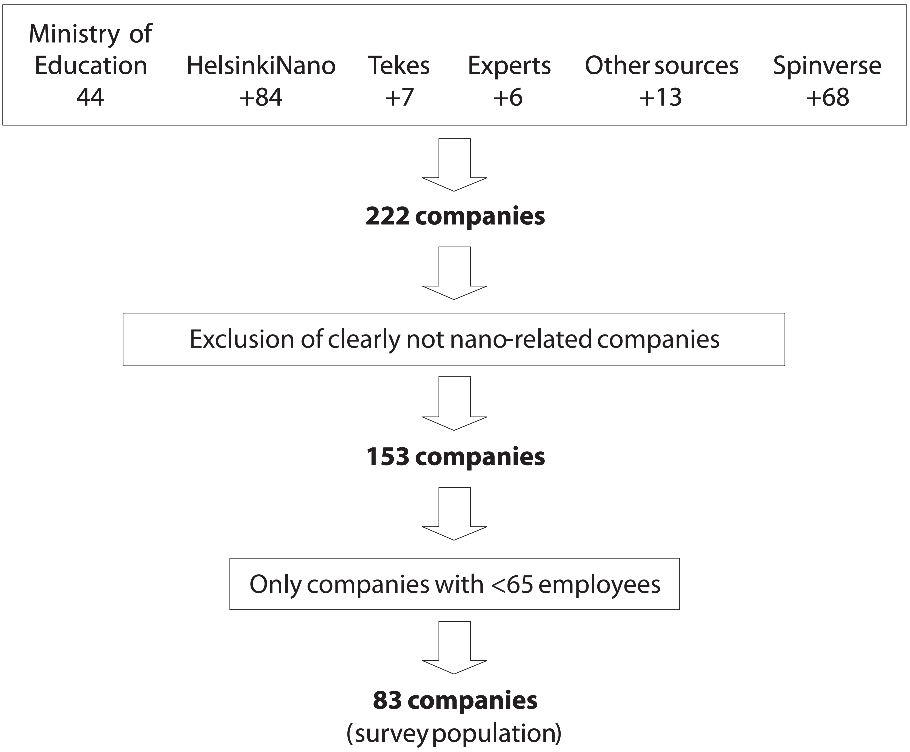
"Commercialising nanotechnology in a traditional industry – The case of glass-processing and construction in Finland"
Palmberg, C. (2008)
ETLA Discussion Papers (forthcoming in 2008)

The transfer of knowledge between researchers, companies and other actors throughout the social networks is a necessary but insufficient prerequisite for the commercialisation of nanotechnology in Finland. Entrepreneurship, new companies, risk funding and the engagement of existing companies as industrialists are also needed. Industry and technology life cycle models predict that new small companies play an especially important role in the early and uncertain phase of emerging technologies when many possible applications and commercialisation routes are looming. Sometimes, as the case of biotechnology suggests, both new and established companies might co-exist in a symbiotic relationship. In the case of nanotechnology it is still unclear whether new or established companies will take the lead in commercialisation, and their division of labour might vary across countries and application industries. Several different data sources were used to identify nanotechnology-related companies in Finland as illustrated in Figure 10.

From the figure it is evident that while many companies have activity related to nanotechnology only a few are solely focused on nanotechnology (nanotechnology dedicated companies). Out of 222 identified companies 153 have potential nanotechnology-related activity with varying degrees of involvement in developing nanotechnologies.[3]

[3] Compare to the survey undertaken in 2006 by Spinverse which identified 134 companies (see http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/NANO/fi/etusivu.html).

Figure 10 Identifying nanotechnology-related companies



From this population roughly half can be classified as truly nanotechnology-dedicated smaller companies and very intensively involved in nanotechnology R&D or commercialisation. In addition to the identification process, a telephone survey was directed at 83 of these nanotechnology-dedicated smaller companies. Somewhat surprisingly the results indicate that the actual number of such companies is even lower as many of them reported no nanotechnology-related activities. This gives further support to the observations made previously that Finnish nanotechnology is still primarily science- and research- oriented while innovation activity amongst companies in industry is limited.

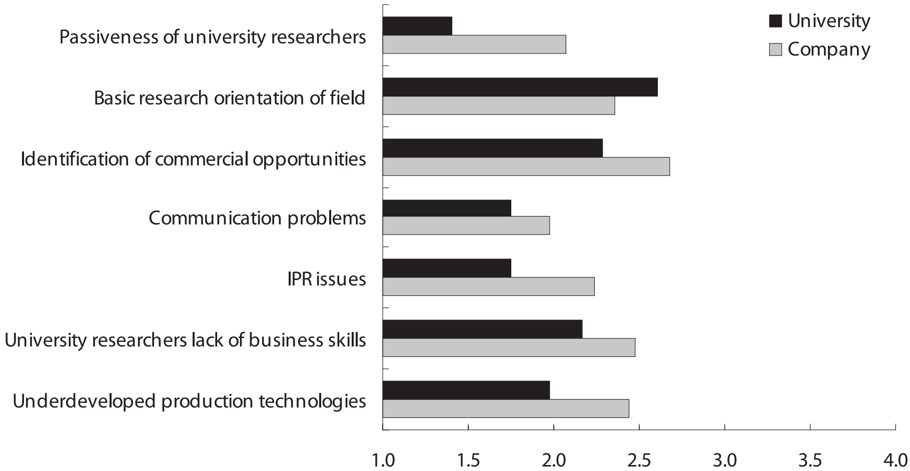
Of the 153 identified companies rather many might not qualify as nanotechnology related ones. While many of the smaller companies might not be active, or might not report nanotechnology activity by their self assessment, the labelling of larger companies as nanotechnology ones is even trickier. Many large companies might indeed have some activities related to nanotechnology but this would hardly classify them as "nanotechnology companies". As a consequence any classification of companies to the field of nanotechnology has to be made with great care and should not be a considered a robust indicator, for example, for the industrial success of this emerging field. The larger companies represent a wide variety of industries such electronics, pulp and paper, metal engineering and chemicals. Later in this report this aspect is discussed in more detail when potential technological linkages between smaller nano-related companies and larger companies are discussed (see Table 2 in Section 8).[4]

In this context the discussion has been about how and why universities and companies differ in their incentives to engage in technology transfer, and how these differences affect the outcomes (for an extensive discussion see Stephan 1996). Universities and companies are two very different environments. The main objective of companies is to carry out applied research for realising innovations. In contrast, universities are by tradition focused on basic research for the general advancement of knowledge and academic degrees. In addition, the immaturity and uncertainties surrounding nanotechnology might lead to further contrasting perceptions of university and company researchers on top of those that already characterise technology transfer across these organisational boundaries and thus introduce new policy challenges.

While nanotechnology-oriented researchers do not appear to identify specific challenges related to technology transfer, there are very clear differences in the perception of university researchers and companies. The basic research orientation of the field, difficulty in identifying commercial applications, and the lack of business and market skills amongst university researchers are challenges that inhibit the transfer of nanotechnology the most. Further, university researchers appear to view nanotechnology as more basic research oriented compared with companies, while the latter highlight the passiveness of university researchers and problems in the identification of commercial applications as the biggest challenges. The interpretation might be that university researchers in this interdisciplinary and natural science-based field are accustomed to doing basic research without immediate requirements for commercialisation. As new policy initiatives are set-up to also engage companies, researchers might have

[4] Spinverse Consulting has also discussed the activities of larger companies in nanotechnology (see http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/NANO/fi/Dokumenttiarkisto/Viestinta_ja_aktivointi/Julkaisut/Nanotech_Finland_Tekes_2007.pdf)

Figure 11 Challenges inhibiting technology transfer by researchers and companies



Note: Scale (1 – Not at all, 4 – Very much) and all differences are statistically significant (at 5% -level).

particular problems in identifying commercial applications, given the early phase of nanotechnology developments.

When the challenges of nanotechnology transfer are related to idea generation, and patenting and licensing as the outcomes of the process some interesting observations emerge. The basic research orientation of the field is an inhibiting factor for idea generation, while challenges in the identification of commercial opportunities and IPR issues have a positive effect of the outcomes, also when various control variables are included.

The basic research orientation as a challenge is compatible with observations about the present early and science-based phase of the development of nanotechnology. However, those researchers that have passed the 'first hurdle' during commercialisation, might be proactively engaged in the identification of commercial opportunities and settling IPR issues and thus also consider these challenges as positive ones in terms of the outcomes. Researchers achieving the outcomes also appear to be more actively engaged with companies through conferences, R&D consulting and bilateral projects with companies, as well as through public technology programmes. This interpretation does not appear to depend on the years elapsed since the researchers received their highest degree in the field (usually a PhD).

In order to gain a better understanding of nanotechnology innovation, applications and commercialisation routes case studies become paramount. Until now empirical research on nanotechnology has mainly been based on aggregate science and technology indicators while the involvement of companies in this technology field remains poorly understood, especially in the context of traditional materials industries.[5] A related project at Etlatieto has contributed with a number of company level case studies in glass-processing in the broader context of the construction industry. The case of glass-processing in construction is particularly relevant due to numerous applications and business opportunities for nanotechnology that now already are materialising.

To a large extent these nanotechnology-related business opportunities relate to the increasing emphasis given to the eco-efficiency of buildings through the use of new, functional materials. Glass-processing is also an area where Finland has a long tradition and deep competencies as an illustration of an application area for nanotechnology outside the commonly touted 'high-technology' industries, such as ICT. At the same time glass-processing is still a very traditional and capital-intensive industry in which products and processes change slowly and in which the diffusion of new technologies is hampered by high fixed investments, low R&D intensity, and conservatism (Manseau ans Shields, 2005).

The benefits of using nanotechnology for glass-processing in construction primarily stems from the self-cleaning new functionalities that can be achieved, even though there are various other applications for example related to energy efficiency. This particular case offers a good example of nanotechnology commercialisation attempts that primarily are driven by small nanotechnology dedicated companies. The interviews of some of the companies, research groups and other stakeholders along this value chain provide interesting snapshots of inducing and blocking mechanisms for nanotechnology, diffusion uptake and commercialisation.[6]

By and large it seems that there is already a relatively well-established, but small, community of researchers within this field in Finland. While individual researchers have pursued various research paths the interest towards nanotechnology applications for ceramics and glass has increased in response both to broader trends and policy initiatives. The broader trends relate to growing demand for

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5 See also *Research Policy* journal's special issue on nanotechnology (*Research Policy 2007 Vol. 36:6*).

6 The interviews cover 16 people of whom 11 represented companies and 5 were researchers from universities or research institutes and others in the public sector.

Figure 12 Nanotechnology and the Finnish glass-processing value chain

Supporting and adjacent industries		Nanotech companies	Machinery suppliers	Intermediate products	Design, maintenance
Glass-processing industry	Raw material suppliers	Glass producers and processors		Sub-system assemblers	Construction companies
Public sector	Universities	Research organisations	R&D programs	Regulators	Industry associations

eco-efficient construction materials, the availability of new instrumentation and techniques, and an increasing awareness of the potentials of new materials. The policy initiatives relate first and foremost to the PINTA programme on clean surfaces commission by Tekes 2002–2006, some of the projects of which were subsequently continued in the FinNano and other programmes.

The PINTA programme appears to have had a particularly important role in influencing and directing the initial R&D, learning and innovation in the early 2000 and has evidently contributed to increasing collaboration and coherence throughout the R&D community in the field. The PINTA programme investigated the usability of functional coatings on many different types of materials but placed particular emphasis on atomic layer deposition (ALD) and sol-gel technologies that are now the two main R&D paths being followed for innovation and applications.

The ALD and sol-gel technologies being developed in Finland have directly benefited from the involvement of a couple of early lead user incumbent companies. A general inhibiting factor, however, seems to be the lack of such lead-user companies in the R&D community. The glass-producing segment of the value chain, as the most obvious entry point for new nanotechnology dedicated companies, is highly concentrated and dominated by a few multinational companies that master the capital intensive flat-glass process. Further downstream in the glass-processing and sub-system assembler segments there is more fragmentation, while concentration again increases amongst the construction companies that represent the system integrators and primary users for nanotechnology enhanced functional coatings for glass.

The concentrated nature of the glass-producing segment inhibits entrepreneurial experimentation. There is less room for smaller glass-producers that could provide a stepping stone for pilot production towards full industrial scale with large and profitable volumes. This same problematic characterises a possible entry further downstream, closer to the construction company segment. Meanwhile it seems that the companies populating the intermediate and more fragmented glass-processor and sub system assembler segments of the value chain lack in-house R&D resources and risk-taking capability to emerge as the lead users for these new technological solutions. Entrepreneurial experimentation is particularly challenging to fulfil due to the very different nature of science-based nanotechnology compared to the traditional glass-processing and construction industries, in which technology change has first and foremost been incremental.

Main conclusions from this section

- There are potentially some 153 nanotechnology-related companies in Finland, half of which are smaller nanotechnology dedicated ones
- Upon close inspection surprisingly many of the small companies do not regard themselves as nanotechnology-related
- The definition of nanotechnology-related companies is tricky in practice (especially in the case of larger companies) and might not be a reliable indicator to guide policy
- There are significant differences between researchers and companies' perceptions on challenges of technology transfer, especially concerning the identification of commercial applications
- Public technology programmes appear to have opened up new commercialisation routes
- The lack of new small, and the involvement of established, companies as lead-users appears to be a problem at least in some application areas

8 Nanotechnology linkages throughout Finnish industries

Based on:
"Identifying nanotechnological linkages in Finnish economy – An explorative study"
Nikulainen, 2007b
ETLA Discussion Papers no. 1101

"Commercialising nanotechnology in a traditional industry – The case of the glass-processing and construction in Finland"
Palmberg, 2008
ETLA Discussion Papers (forthcoming in 2008)

As discussed earlier in this report, nanotechnology seems to have a variety of potential commercial areas in various industries. For this reason it is useful to identify in greater detail the potential diffusion paths for nanotechnology on a company level in Finland. By shedding more light on the interaction in the private sector the potential of nanotechnology as a source of industrial renewal is assessed. To understand the dynamics in the private sector activities in nanotechnology, the main emphasis was on identifying the nanotechnology-dedicated smaller companies, looking at their technological profile and understanding how these companies are potentially linked to larger established companies and industries.

A crucial step in the analysis was the identification of smaller nanotechnology-dedicated companies. These smaller companies were identified by using the list of companies collected for the project (see Figure 10). There were 83 smaller nanotechnology companies. Based on this data collection it is evident that identifying nanotechnology related activities is not only difficult in patent and publication analysis, but also at the company-level. In addition, many of the smaller nanotechnology-dedicated companies have no patents. Thus there are 31 smaller nanotechnology-dedicated companies with at least one published patent application each.

A revealed technological advantage -index (RTA-index) is used to identify the comparative advantages of Finland, smaller nanotechnology-dedicated companies, nanotechnology-related academia and, as a reference group, smaller biotechnology-dedicated companies (see Table 1). By this explorative approach, we aimed to establish potential nanotechnological linkages between the different groups.

Table 1 Revealed Technological Advantage -index

		Finnish nano-community		
	Finland vs. World *n=24 019*	Small nano-comp. vs. Finland *n=167*	Nano-academia vs. Finland *n=262*	Small bio-comp. vs. Finland *n=255*
Electrical engineering	**1.53**	0.21	0.28	0.15
Instruments	0.68	**2.81**	**3.02**	**2.45**
Chemicals & pharmaceuticals	0.42	**2.08**	**2.89**	**5.54**
Process engineering	**1.49**	**2.01**	**1.34**	0.62
Mechanical engineering	0.93	0.15	0.12	0.07
Cons. goods and civil eng.	**1.10**	0.09	0.22	0.06

The RTA-index reveals that the smaller nanotechnology-dedicated companies and academia have a similar technological profile. In addition, the smaller nanotechnology-dedicated companies are activity in technological areas where Finland is technologically specialised. And finally nanotechnology seems to be better aligned with the Finnish technological specialisation when compared with biotechnology.

While the RTA-index provides general comparative insights about linkages and the alignment of nanotechnology with the overall technological specialisation of Finland, a more detailed analysis provides further information. By comparing patenting activity between the smaller nanotechnology-dedicated companies and overall patenting activity in Finland, the potential nanotechnology linkages, based on similarity in patenting, can be identified between smaller nanotechnology-dedicated and larger established companies. The variety in the industries that hereby are highlighted range from high-tech, such as electronics and pharmaceuticals, to more traditional industries, such as paper and forest, and metal engineering (Table 2).

Even if the potential linkages can be established, the ability of the larger established companies to utilise these nanotechnology linkages is unclear. Therefore by analysing the absorptive capacity of the established companies through a proxy, in this case the R&D intensity of a company, this paper provides more insights to these potential linkages. It seems that established companies with potential nanotechnology linkages have a higher R&D intensity when industry specificities are taken into account. This suggests that the companies with links

Table 2 Industries with potential nanotechnological linkages

Industry	No. of companies	%
Electronics	3	6
Foodstuff	4	8
Energy	1	2
Chemical and pharma	9	18
Metal engineering	12	24
Paper and forest	5	10
Miscellaneous	6	12
Packing	1	2
Construction	4	8
Textiles	1	2
Wholesale	2	4
Services	2	4
Total	50	100

to nanotechnology are better placed to utilise external sources of knowledge than other established companies without these links.

Overall it thus seems that the technological activities of the Finnish nanotechnology community are linked to the overall technological strengths of the Finnish economy. When compared to biotechnology this impression is reinforced. Further, nanotechnology seems to be linked to a variety of companies having the ability to utilise external sources of knowledge. One such link relates to glass-processing and the construction industries, the case studies of which can throw some further specific insights on opportunities and barriers related to commercialization of nanotechnology.

The growing demand for eco-efficient construction materials has had a significant general influence on incentives to identify and developing linkages between nanotechnology, glass-processing and the construction industry. This relates directly to new legislation that is in the process of being enacted in the construction industry and that also gives rise to new business opportunities for companies. An underlying enabler for developing relevant technologies for these business opportunities has also been certain patented process inventions which have been largely developed in Finland. The inventions have directly benefited from new types of interdisciplinary collaboration and instruments that can be attributed to nanotechnology developments.

The PINTA programme appears to have had a particularly important role in influencing and directing the initial R&D, learning and innovation processes in the early 2000s and has evidently contributed to increasing collaboration and coherence throughout the R&D community in the field. A new programme named Functional Coatings is presently being initiated by Tekes for 2007–2013. Even though the public R&D programmes have been facilitating in this context some concern was also raised that applications in, and linkages to, high-technology industries have been prioritised too much and at the cost of many promising areas in the more traditional industries such as construction. One reason for this might be that natural scientists, especially in physics, might be preoccupied with applications in the electronics industry almost by default. Further, the cross-pollination between nano- and biotechnology has tended to be excluded in the nanotechnology dedicated programmes to date with some inhibiting effects on diversification towards, for example, bioactive glass and other new and interesting areas.

Sometimes linkages might not emerge due to underdeveloped market formation processes, especially in the early phases of commercialisation when the home market can be especially important. In the case of nanotechnology and the glass-processing industry the very early an experimental nature of developments has implied that the market formation phase likewise is in a very early phase. The problem is that the cost-performance ratio of new nanotechnology enhanced functional coatings for glass is unsettled, especially for smaller production volumes. Some issues related to occupational hazards and unintended interactions between raw materials also have to be investigated further, suggesting that environment, health and safety (EHS) issues also need attention.

The construction companies, which eventually procure and integrate various construction elements and sub-systems, have to engage in detailed cost-benefit analysis that covers the whole life cycle of a new building. Even though nanotechnology-enhanced functional coatings already do add value to glass the transformation of this value as higher costs of buildings to the end-users requires better communication in this new market. The communication of the benefits and the legitimation of nanotechnology enhanced functional coatings require more and coordinated efforts that should also involve industry associations, architects, civil engineers and other important stakeholders. In other words, the degree to which nanotechnology will create linkages throughout Finnish industries will also depend on the degree to which new partnerships can be established; this observation is very much in line with the complementarities that an emerging general purpose technology requires for its further diffusion throughout economies.

The main conclusions of this section

- The innovative activities of nanotechnology-related researchers and companies appears to match the overall technological specialisation of Finland
- The compatibility between innovative activities and the overall technological specialisation of Finland appears to be greater for nanotechnology compared to biotechnology
- Finnish nanotechnology activities appears to have potential, or already established, linkages to a broad range of industries, both of a high-tech and more traditional nature
- The existing companies that appear to link more closely to nanotechnology are also characterised by higher average R&D intensity as one indicator for higher absorptive capability
- Public technology programmes can facilitate nanotechnology linkages throughout industries although attention must also be given to the formation of test-trial markets, regulatory issues, new partnerships and sufficient critical mass

9 Conclusions and policy observations

To conclude this report we suggest a simple SWOT analysis of the potential of nanotechnology to renew industries in Finland, also as a device for summarising the main findings of the project as a whole and assigning value labels to some of these findings.

A SWOT analysis singles out strengths, weaknesses, opportunities and threats pertinent to a particular area or activity, in this case applied to nanotechnology-related innovation activities in Finland. While some of these strengths can be nurtured further, and some of the weaknesses might be strengthened through policies, it is also clear that many of the opportunities and threats significantly depend on global nanotechnology developments. In this sense it should be clearly stated that a further analysis of nanotechnology developments in Finland must be undertaken that also places these developments in a broader international and comparative perspective.

The **strengths** of Finnish nanotechnology developments relate to the dedication that policymakers and other actors are showing toward this emerging field, and to the compatibility of this field with existing areas of technological strengths. Finnish innovation policy is renowned for reaching consensus on broader aims and for the ability to quickly activate researchers, companies and other stakeholders towards this end. While there is a continuous debate on the details of priority-setting related to nanotechnology (and its relationship to biotechnology) it appears that the FinNano programmes have also achieved this consensus as a dedicated nanotechnology programme. Finnish nanotechnology R&D investments are naturally miniscule in international comparisons. However, they are relatively speaking quite significant. This dedication to R&D can be considered a specific strength of Finnish nanotechnology developments.

Set against the global nanotechnology race key questions for future developments are how these relatively high nanotechnology R&D investments can be leveraged further towards areas of technological and industrial strengths through the engagement of new and existing companies, as well as how future policies in the field will be implemented. Priority-setting will be the key issue, not least due to the convergence between ICT, bio- and nanotechnologies that some analysts are predicting. The NANOREF project has demonstrated that present nanotechnology developments in Finland appear to be relatively well aligned with these technological and industrial strengths, and even more so for nanotechnology when compared with biotechnology. In some ways these patterns

Strengths • When R&D expenditures and publications are measured relative to the size of the population Finland emerges as a country with significant activity • The innovative activities of nanotechnology-related researchers and companies appears to match the overall technological specialisation of Finland • The compatibility between innovative activities and the overall technological specialisation of Finland appears to be greater for nanotechnology when compared with biotechnology	**Weaknesses** • Nanotechnology developments in Finland are still very science-oriented while innovation activity amongst companies is limited • The transfer of nanotechnology from public sector research to industry faces various challenges • Research networks are still very fragmented • Upon close inspection surprisingly many of the small companies do not regard themselves as nanotechnology-related • The lack of new small, and the involvement of established, companies as lead-users appears to be a problem at least in some application areas
Opportunities • Some regional clusters are emerging with the biggest concentration in the Helsinki area • Expected commercialisation durations (from idea to market) are shorter in the more traditional industries of metals and engineering, foodstuffs, pulp & paper, energy and construction • Finnish nanotechnology activities have potential, or already established, links to a broad range of industries, both of high- and low-tech nature • The existing companies that appear to link more closely to nanotechnology are also characterised by higher average R&D intensity as one indicator for higher absorptive capability	**Threats** • Public technology programmes can facilitate nanotechnology linkages throughout industries although attention also has to be paid to the formation of test-trial markets, considerations of regulatory issues and the importance of new partnerships and sufficient critical mass • Securing continuity in public financing • Uncertainties of global nanotechnology developments and public perception; environmental, health, safety and ethical issues • Hype and the global nanotechnology race

reflect path-dependency and the general purpose nature of nanotechnology. In so far as this is the case care should be taken to ensure that these naturally occurring linkages are analysed, understood and supported further.

Despite the relatively good alignment of nanotechnology with the technological and industrial strengths of Finland a whole range of challenging questions remain to be considered. First of all, how should the interrelationships between bio- and nanotechnology be handled, especially given the difficulty Finland has experienced in commercialising biotechnology? It is inevitable that these two technology fields will cross-pollinate and benefit from each other while it is also clear that some of the greatest uncertainties and risks characterising nanotechnology developments can be found at this intersection. A second question is whether there should be a continuation of nanotechnology dedicated programmes or whether it would be better to focus on convergent application areas further downstream, such as, nanoelectronics, nano-optics, nanobiopharmaceuticals, nanomaterials, once the initial consensus and activation level has been achieved? The concept 'nanotechnology' might be a temporary one and eventually become obsolete as nanotechnology developments spread and become distributed across a whole range of different industries. A third question is what balance should be struck between supporting basic, curiosity-driven and more applied research?

Curiosity-driven basic research is of importance for sustaining a high level of absorptive capability especially in the case of an emerging general purpose technology, such as nanotechnology, for which there is significant uncertainty regarding viable commercialisation paths. Nonetheless, the NANOREF project has also highlighted the science- and research-oriented nature of present Finnish nanotechnology, considered here as **weaknesses** from the viewpoint of rapid nanotechnology innovation and commercialisation. The science- and research oriented nature of nanotechnology thus has to be acknowledged by policy. A major challenge relates to bridging the gaps between researchers and companies in their viewpoints of the nature of nanotechnology. The research community is traditionally oriented towards the fundamentals of nanoscale engineering while companies have difficulties in identifying those research tracks that might be commercially most viable. The FinNano program commissioned by Tekes takes an active stance towards mitigating some of these problems and it also seeks to involve companies. This concerns especially the more established companies which can act as industrialists and help to scale up research to industrial production and to provide complementary technologies and other competencies that are required for commercialisation.

On the research side it appears that networks are still very fragmented. The issue of interdisciplinarity raises specific challenges in so far as innovation policy initiatives, such as the FinNano programmes, can facilitate collaboration between physicist, chemists and biologists. However, interdisciplinarity is not the only issue of. Finland still hosts a limited number of smaller nanotechnology-dedicated firms. These types of firms can often act as important intermediaries between the research community and larger established companies, or industrialists, during the commercialisation of emerging technologies. They might facilitate a better identification of viable commercialisation opportunities of research and also carry some of the risks that established companies might not be able to handle in a flexible way. One of these risks relates to the widespread applicability of nanotechnology, whereby it is unclear which specific application, in the end, can provide viable commercial opportunities. As a consequence a larger number of these smaller companies would also collectively provide better support for experimentation in many application areas. All of these problems are accentuated by a lack of risk-taking established companies in some application areas of nanotechnology, especially in the more traditional industries.

The emergence of regional clusters, with a relatively clear division of labour, and the diversity of technological and industrial strengths of the economy, seems to provide the greatest **opportunities** for nanotechnology developments. Finland now hosts a number of regional clusters in the close vicinity of polytechnics and technical universities some of which also offer nanotechnology-related curriculum and dedicated research infrastructure. Despite the global nanotechnology race there are several interesting examples of how technological and eventually industrial strengths have been built also with small absolute resources, not least in the case of mobile telecommunications in Finland. These regional clusters should thus be supported further in a balanced way while also ensuring that overlapping activities can be avoided and that collaboration can be extended. The Technical Research Centre (VTT) can play an important role in this context owing to its critical mass in terms of size and coverage of many application areas of key importance for nanotechnology.

The diversity of Finnish technological and industrial strengths – combined with a consensus-building ability and a certain degree of agility – are also conducive for general purpose technologies, such as nanotechnology. Despite the rapid outgrowth of a highly competitive mobile telecommunications industry (with Nokia in the lead) Finland still hosts a whole range of more traditional industries that draw on competencies in chemicals, materials, machinery, process automation, biotechnology and other areas that can be highly complementary to nanotechnology. The NANOREF project has highlighted some already existing or potential linkages between nanotechnology and other fields, and pointed to the absorptive capability that many of the established companies in these areas appear to have. The analyses have also suggested that commercialisation durations for nanotechnology might be shorter in some of the more traditional industries. Linkages between nanotechnology and some of the high-volume traditional industries, such as pulp & paper, metals, machinery, and construction might be the most promising way forward. At the same time the importance of ICT applications should of course not be neglected.

Nonetheless, while there are many opportunities there are also **threats** to steer clear from. As already suggested Finnish nanotechnology developments are still very science- and research- oriented even though nanotechnology also, generally speaking, is an application-driven field. Thus, it might be particularly challenging to engage researchers in natural science fields, for example theoretical physicist, in application areas of relevance, for example, to the pulp & paper industry that traditionally has been the domain of forestry engineers. The specific case of the use of nanotechnology in glass-processing for applications in the construction industry also highlighted a range of challenges in this context. Tight price competition, a preoccupation with productivity increases and high production volumes might not be compatible with experimentation in, and the establishment of test-trial markets for nanotechnology due to high start-up and other fixed costs. Nanotechnology has also yet to prove its value-added over many of the more traditional, but nonetheless highly functional and cheaper materials, such as glass, ceramics etc. Further, concentrated industrial structures, lack of facilitating regulations, and a certain conservatisms of traditional industries might also play against new nanotechnology applications.

Finally, as was also highlighted in the beginning of this section, nanotechnology is indeed an emerging technology characterised by a global R&D race, hype, many uncertainties and open issues that are beyond the sphere of influence of any one country. ICT has been a technology field connected with very positive connotations, not least due to the policy emphasis on knowledge economies, information societies etc. for which information technology applications often have been considered the backbone. Even though biotechnology has also achieved some success, the prolonged, important but partly also misconceived debate about genetically modified organisms (GMOs), has been a major barrier for its further industrial development and success until the present day. Nanotechnology is in the early phases of its diffusion path and issues related to its environmental, health, safety and ethical sustainability are only surfacing. International forums now exist to support the balanced development of this emerging field but some backlash is bound to occur as the public becomes increasingly engaged. It is important that Finland also follows, and contributes to, these debates and also considers alternative scenarios for unlocking the economic and societal opportunities that nanotechnology has to offer in the longer run.

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APPENDIX

Policy-related definitions of nanotechnology in the US, EU and Japan

	Definition
US: National Nanotechnology Initiative (2001–)	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, modeling, and manipulating matter at this length scale.
EU: 7th Framework Programme (2007–)	Generating new knowledge on interface and **size-dependent phenomena**; nano-scale control of material properties **for new applications**; integration of technologies at the nano-scale; self-assembling properties; nano-motors; machines and systems; methods and tools for characterisation and **manipulation at nano dimensions**; nano precision technologies in chemistry for the manufacture of basic materials and components; impact on human safety, health and the environment; metrology, monitoring and sensing, nomenclature and standards; exploration of new concepts and approaches for sectoral applications, including the **integration and convergence of emerging technologies**.
Japan: Second Science and Technology Basic Plan (2001–2005)	Nanotechnology is an **interdisciplinary** S&T that encompasses IT technology, the environmental sciences, life sciences, materials science, etc. It is for **controlling and handling atoms and molecules in the order of nano (1/1 000 000 000) meter** enabling discovery of **new functions** by taking advantage of its material characteristics unique to nano size, so that it can **bring technological innovation in various fields**.

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