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Emergence of Nano S&T in Germany. Network Formation and Company Performance.

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Abstract

This article investigates the emergence of nano S&T in Germany. Using multiple longitudinal data sets, we describe the complete set of research institutions and companies that entered this science-based technology field and the development of their inter-organisational networks between 1991 and 2000. We demonstrate that the co-publication network is a core-periphery structure in which some companies were key players at an early stage of field formation, whereas later universities and other extra-university institutes took over as the central drivers of scientific progress. Further differentiating among types of firms and research organisations, we find that in the co-patent network collaboration is most intense between high-technology firms and use-inspired basic research institutes. While many companies co-patent with several universities or other public institutes, some succeed in establishing almost exclusive relationships with public research units. It is shown that co-patent and co-publication ties are most effective at strengthening the technological performance of firms, that multiple interaction channels increase company performance, and that companies benefit from collaborating with scientifically central universities and institutes.

Keywords

nanotechnology, network analysis, company performance, public research sector, innovation system, science industry cooperation, Germany

1 Introduction

Over the last two decades, nano science and technology (nano S&T) has emerged as a big field of research, spanning both scientific disciplines and technological sectors. Nano S&T refers to nano-scale phenomena, i.e. materials, structures and processes with a length of 1 to 100 nanometers whose properties depend on this length scale. Various scholars have already addressed the emergence of this thriving field by either focusing on bibliometric indicators (Hullmann/Meyer 2003; Meyer 2001; Meyer/Persson 1998), combined bibliometric and institutional analyses (Darby/Zucker 2003; Zucker/Darby 2005; Heinze 2004; 2006) or detailed technical essays (Ratner/Ratner 2003; Rieth 2003; Bachmann 1998).

This article investigates the emergence of nano S&T in Germany, a major contributing country. Using multiple longitudinal data sets, we describe the research institutions and companies that have entered this science-based technology field, how they developed various types of network ties over time and which types of inter-organisational patterns are discernible in an early phase of field formation. While many studies point to the relevance of inter-organisational ties in processes of technological innovation (Valentín 2002; Liebeskind et al. 1996; Freeman 1991), we offer detailed analyses as to the effect of network ties on company performance in the nano S&T field.

Our analyses build on a rich set of empirical data, both quantitative and qualitative. On the quantitative side, we refer to extensive time series of publication, patent, and collaborative research project data, covering about 350 research organisations and companies in Germany over a time span of ten years. On the qualitative side, we use insights from about 40 semi-structured interviews conducted between 2004 and 2006, including major stakeholders of the emerging field, such as company representatives, researchers across multiple disciplines, venture capitalists and science administrators (Heinze 2006: 254-282, 293-294; Heinze/Kuhlmann 2006). Data retrieval was made possible by two sophisticated S&T field delineations, one for publications, another for patents (Noyons et al. 2003).

The text begins with a short review of the nano S&T field emergence. Here, we briefly introduce major research breakthroughs, describe the enormous thematic breadth of the field and comment on the strong correlation between publication and patent dynamics (Chap. 2). Then we examine the core-periphery structure of the German co-publication network and determine relevant meso and micro structures of the German co-patent network. We find that network densities between high-technology firms and use-inspired research institutes are much higher than other other type of dyadic relationships. By applying block model analysis to the co-patent data, we identify two types of micro interaction pattern: first, exclusive company-institute relationships, second, a more competitive multiple company – multiple institute model (Chap.3). The fourth chapter turns to company performance as measured by patent applications. We test which kind of collaborative ties are most consequential in strengthening technological capabilities of firms, and which other network measures explain company performance (Chap.4). The final section discusses the findings and suggests directions for further research (Chap.5).

2 Characterising the Emergence of the Nano S&T Field

The nano S&T field developed from a number of research breakthroughs in applied physics, macromolecular chemistry, and more recently, in electronics. In the late 1950s, physicist and Nobel laureate Richard Feynman pointed to the enormous technological possibilities that accrue from the manipulation of matter at the atomic and molecular level, such as huge amounts of data storage and transfer, but also construction of energy-efficient molecular machines (Feynman 1960). Feynman's ideas were visionary, because the spectroscopic capabilities for R&D on the nano scale were still lacking. The situation changed when Gerd Binnig und Heinrich Rohrer invented the Scanning Tunnel Microscope (STM) at IBM Research Center in Zurich in 1981 (Binnig/Rohrer 1982a; Binnig/Rohrer 1982b), an invention that won both physicists the Nobel Prize in 1986 and which was further elaborated into the Atomic Force Microscope (AFM) several years later (Binnig et al. 1986; Binnig et al. 1987). Both STM and AFM are non-optical microscopes which employ principles of quantum mechanics. In contrast to conventional electron microscopes, they attain extremely high-quality resolution at the atomic level. While STM uses the so-called tunnel effect in conductive materials at the nano scale, the AFM works well with non-conductive matter which makes it an excellent tool for studying live biological samples.

While applied physics approached the atomic scale by means of new microscopy instruments (top-down), the synthesis of two new carbon materials (bottom-up) brought considerable dynamics into the macromolecular chemistry branch of the nano S&T field. In 1985, Richard Smalley, Richard Curl (Rice University) und Harold Kroto (University of Sussex) discovered C-60 carbon nanoballs (known as Buckminster Fullerenes) that have interesting chemical and physical properties (Heath et al. 1985; Kroto et al. 1985). Half a decade later, Sumio Iijima (NEC Corporation) developed carbon nanotubes and processes for their production (Iijima 1991; Iijima et al. 1992). Both breakthroughs opened up new research areas, an important proportion of which deal with electrical properties of these new carbon structures. Among the major recent developments building on these new materials is Cees Dekker's (Technical University Delft) development of a nanotube transistor at room temperature in 1998 (Tans et al. 1998), but also a nanotube-based circuit devised by Stanley Williams and Philip Kuekes (Hewlett Packard) one year later (Collier et al. 1999).

The scientific dynamics initiated by various research breakthroughs have been accompanied by developments to establish the nano S&T field. Starting in the early 1990s, dedicated research journals were founded to absorb the increasing number of scientific findings, such as *Nano Letters* (American Chemical Society), *Journal of Nanoscience and Nanotechnology* (American Scientific Publishers), *Journal of Nanoparticle Research* (Kluwer Academic Publishing) or *Nanotechnology* (Institute of Physics). Likewise, the number and thematic breadth of conferences and workshops on nano-scale phenomena has grown exponentially in the last decade. In addition, an increasing number of universities are offering courses, classes and degrees in the field, mostly in the physics or engineering departments. Examples are Rice

University,[1] MIT,[2] Cornell University,[3] University of Washington,[4] Technical University Delft,[5] University of Würzburg,[6] University of Kassel,[7] or University of Saarland.[8] Finally, several intermediary associations bridging industry and academia have set up nano S&T sections, such as the Swiss Society for Optics and Microscopy[9] and the German Society for Chemical Engineering and Biotechnology.[10]

The formation of the nano S&T field builds on the availability of substantial R&D resources. STM and AFM facilities are topical in this respect, but also MEMS and nano-lithography systems are extremely expensive, both in acquisition and in maintenance costs. Several countries have launched dedicated nano S&T funding programmes in the late 1990s and early 2000s to meet these investment needs and to ensure international competitiveness of their research institutions. The largest effort has been undertaken by the U.S. administration which set up a National Nanotechnology Initiative in 2000, an important part of which includes a multi-year funding of infrastructure labs across the country, the so-called NNIN sites.[11] In Europe, the Research Framework Programmes of the European Commission provided between 1994 and 2002 about € 320 m for nano scale research, and made the field a thematic priority between 2003 and 2006 with a total budget of € 1.3 bn.[12] Including national research programmes of EU-15 member states, the total sum of public and private R&D money spent on nano S&T research in Europe equals that of the U.S., amounting to roughly € 3 bn in 2004. However, in Europe the share of public investment is substantially higher than that of the private sector (60 to 40), while companies in Japan and the U.S. have invested more than half of the resource base (Hullmann 2005).

The field of nano S&T is characterised by an enormous thematic breadth. A quantitative analysis of relevant publications shows that the most important sub-disciplines are applied physics, material science, physical chemistry, physics of condensed matter, chemistry and molecular biology. While the share of material science, polymer chemistry and chemistry has increased between 1994 and 2003, publications in physics and biology have decreased in relative terms. With respect to publication output, to use a phrase coined by Feynman, nano S&T appears much more than just a "new field of physics" (Figure 1).

Likewise, nano S&T patent applications are filed in a broad range of technical areas: relevant patents are found in all eight sections of the International Patent Classification (IPC). On a

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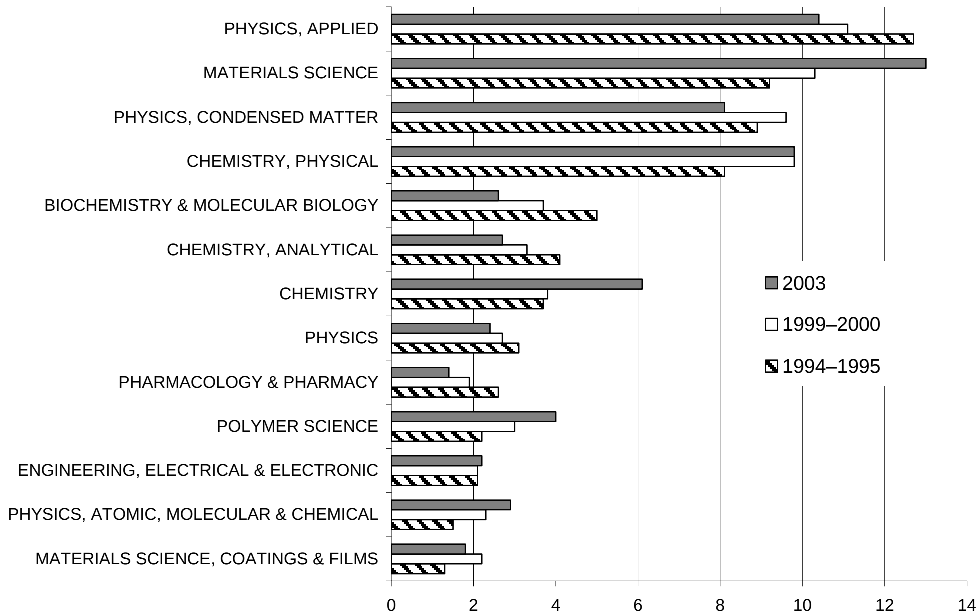
1 http://cnst.rice.edu/.
2 http://nanoweb.mit.edu/.
3 http://www.nbtc.cornell.edu/.
4 http://www.nano.washington.edu/index.asp.
5 http://www.ns.tudelft.nl/.
6 http://www.physik.uni-wuerzburg.de/nano/.
7 http://84.131.141.85/info/studienganginfo.shtml.
8 http://www.uni-saarland.de/fak7/physik/Welcome.html.
9 http://www.ssom.ch/index.html.
10 http://www.dechema.de/nanotechnologie.html.
11 http://www.nnin.org/.
12 http://www.cordis.lu/nanotechnology/.

four-digit level, the top 3 IPC classes are characterisation of chemical and physical properties (G01N), preparations for medical, dental or toilet purposes (A61K) and semiconductor, solid state devices (H01L). By far the largest IPC section is chemistry (ca. 40%) which includes, for instance, coating metallic materials (C23C), measuring and testing processes involving enzymes and micro-organisms (C12Q), compounds of non-metallic elements (C01B) and peptides (C07K). The numbers reported here refer to EPO and PCT patent applications (Heinze 2004; 2006; Noyons et al. 2003), and similar results have been reported elsewhere (Hullmann/Meyer 2003; Darby/Zucker 2003).

Figure 1: Share of Sub-disciplines in Nano S&T, 1994-2003 (per cent)

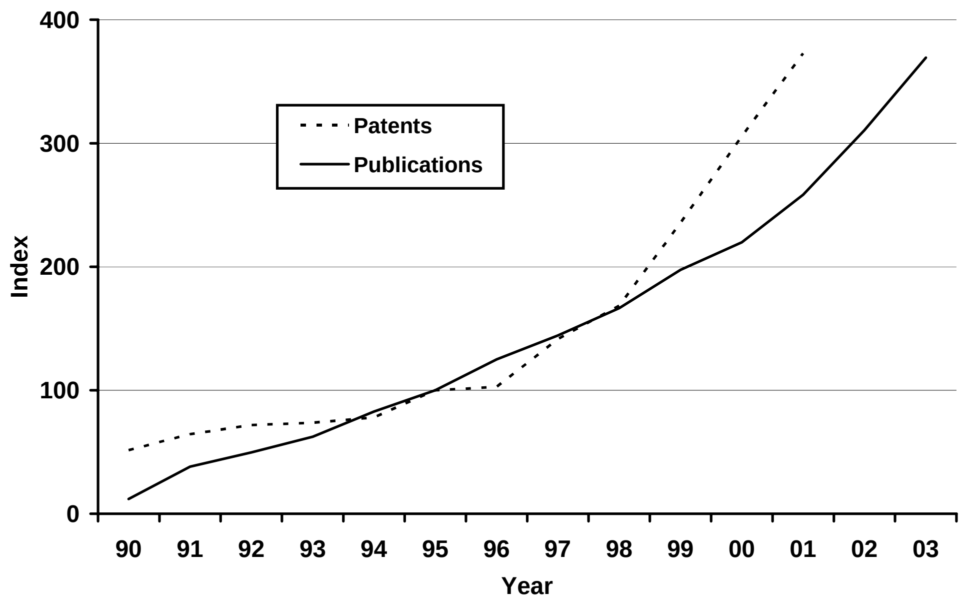


Source: Calculations by author using SCI (Host STN). Smaller sub-disciplines (below 2%) are not displayed.

The various disciplines and technical areas demonstrate that nano S&T is not a coherent field, but cuts across established fields of research and technology. Similarly, most nano-S&T-related commercial applications are embedded in already existing products and processes. Hence, there is no single nano S&T market, but many submarkets. For instance, nanoparticles are used for scratch-resistant and light-resistant coating of windows and carbodies, while light-sensitive nanoparticles are embedded in solar cells. In the aircraft and space industry ultra-light but extremely hard nanomaterials are being tested. In the construction industry, protection against corrosion or calcification is achieved through ultra-thin functional multi-layers on metallic applications or shower walls. Sun creams contain zinc or titan oxide particles that help protect human tissue against UV beams. Nanostructures are also used in optical applications, such as light-emitting diodes. A first serious estimation of the scope and size of such worldwide markets was introduced by an expert group of the German Engineering Association (Luther/Malanowski 2004). The authors argue that the next years will witness dynamic market growth in nanomaterials, such as nanotubes, polymer composites, but also aerogels, organic semiconductors and inorganic nanoparticles. Likewise, medical, pharmaceutical and cosmetic applications are regarded as areas with growth potentials.

While thematic and sectoral breadth is an important characteristic of the nano S&T field, a bibliometric analysis reveals another interesting feature: dynamics of both publications and patent applications follow the same growth path and are highly correlated over time. As shown in Figure 2, worldwide publications have grown at an annual growth rate of 20 percent since the early 1990s. At the same time, the number of patent applications has grown considerably, particularly after 1995. Schmoch (2003) demonstrated that the same pattern of parallel science and technology dynamics is also observed in biotechnology, another science-based technology field. From the findings in Figure 2, we conclude firstly that technological progress in the nano S&T field is fuelled by the underlying research base, most importantly universities and public extra-university research organisations; and secondly that considerable knowledge transfer seems to take place between the public research sector (where most publications originate) and the private company sector (where most patent applications originate).

Figure 2: Patent applications and Publications in Nano S&T, 1984-2003



Source: Calculations by author using SCI, WPI (Host STN). Index 1995 = 100.

The following chapter explores the interaction of public research and private companies in the emerging field of nano S&T in more analytical detail and empirical depth. Using multiple longitudinal data sets, we describe for Germany as one of the major contributing countries the development of inter-organisational networks between research organisations and companies. We examine various network ties, such as co-patents or co-publications, and analyse typical structures of these network configurations.

3 Network Formation between Public Research Organisations and Companies

Our investigation addresses two aspects with regard to the emergence of an organisational field. First, we describe how established organisations, both in the public and the private sector, engage in nano S&T activities, such as research or technology development. Secondly, new actors appear, such as new research institutes or start-up companies that coordinate their action with incumbent organisations via competition or cooperation. We define an organisational field as a set of actors that engage in related activities while they are anchored in societal domains with different institutional logics (Kaufmann/Tödtling 2001). In the case of science-based technologies, organisational fields span societal domains such as the science system, the political system, the business world, tertiary education or the world of law and legislation (Heinze 2005). As illustrated in the preceding chapter, the nano S&T organisational field emerged when research breakthroughs invigorated applied physics (e.g. discovery of STM/AFM) and opened up new research territory in chemistry (e.g. discovery of Fullerenes), when progress in science and engineering created new technological and commercial opportunities for private companies (e.g. application of nanotubes in semiconductor devices), and when policymakers channelled substantial resources into the S&T infrastructure to promote technological innovation (e.g. nano S&T priority in European FP6).

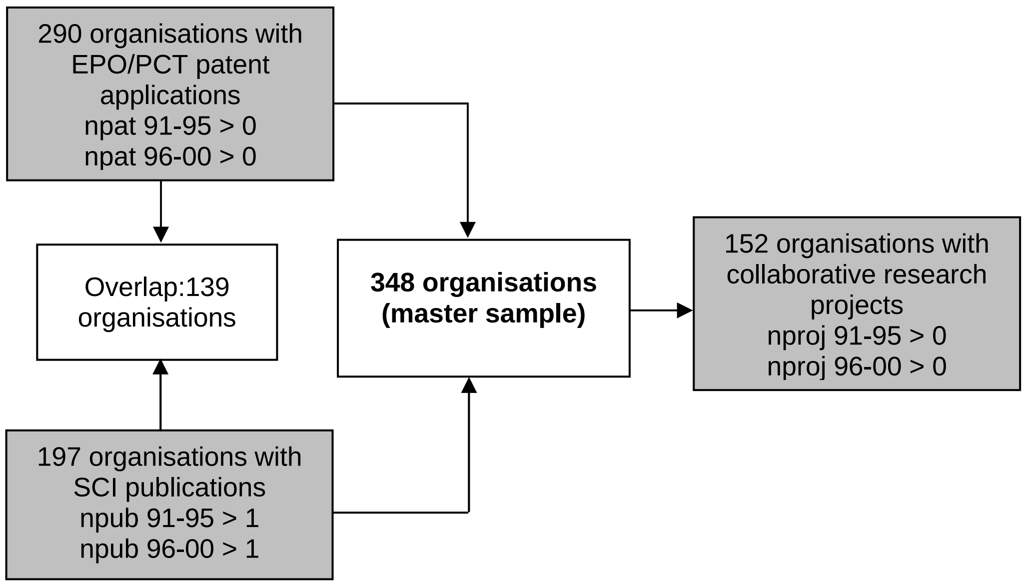
A number of interesting studies have dealt with the emergence of specific organisational fields (Scott et al. 2000; Thornton 2004) or sectoral innovation systems (Malerba 2000; Carlsson 2002). But despite their focus on relations between different actors and organisations that constitute a recognised arena of social and economic activity, these studies neither analysed the interactions of multiple, overlapping networks in longitudinal research designs, nor did they examine the effects of these networks on organisational performance. McPherson et al. (2001) note that there are few studies that employ longitudinal data to analyse networks. Burt (2000) voiced a similar concern that most studies of network structure are cross-sectional. It was only very recently that Powell et al. (2005) and Evans (2004) illustrated the evolution of inter-organisational networks in biotechnology, and that Burt (2004) presented results on longitudinal manager networks in a large electronics company. Our analyses draw upon insights of these studies, particularly with respect to the link between network dynamics and organisational performance. By examining networks of universities, extra-university institutes and private companies, we focus on linkages between two particular societal domains: the *science system* and the *economic system*.

3.1 Database

At present, it seems methodically almost impossible to map the emergence of an organisational field on a worldwide scale. This holds in particular for big, science-based technology fields that cut across established research areas and industry sectors and, hence, involve a huge number of research organisations and companies. Consequently, we selected Germany as one major player both in nano S&T publication and patent productivity for in-depth analyses: Germany's share in SCI publications is 12 percent (1990-2003), while the share of EPO/PCT patent applications is about 18 percent (1990-2001) (Noyons et al. 2003).

Our database for nano S&T in Germany includes ca. 350 universities, extra-university institutes, incumbent companies and small start-ups. The data set includes two five-year periods 1991-1995 and 1996-2000, and thus covers field emergence already at an early stage. All actors who have either published or patented in these time periods are included and analysed (Figure 3). We examine three types of network ties: co-patents, co-publications and collaborative, applied research projects. In order to fully capture public sector involvement in patenting, we matched inventor names with SCI authors, a method that significantly increased the number of research institutes in the patent database. Table 1 shows the number of companies and research organisations in each dimension and time period.[13]

Figure 3: Sample Selection, Nano S&T in Germany, 1991-2000



Source: Heinze (2006).

13 For methodical details, see Heinze (2006:142-81, 254-275).

Table 1: Number of Organisations in Database, 1991-2000

	Projects 1991–95	Projects 1996–00	Publications 1991–95	Publications 1996–00	Patents 1991–95	Patents 1996–00
Companies	**22**	**47**	**20**	**45**	**62**	**155**
Large corporations	12	26	13)	30	28	58
Small/medium-sized companies	3	15	1	7	2	40
High-tech companies[1]	*18*	*29*	*15*	*31*	*27*	*65*
Low-tech companies[1]	*4*	*10*	*4*	*6*	*14*	*34*
Research Organisations	**80**	**97**	**111**	**150**	**58**	**96**
Universities	46	51	57	60	35	48
Max Planck Institutes	9	11	18	29	6	11
Fraunhofer Institutes	8	12	13	18	5	8
Leibniz Institutes	6	5	3	9	3	7
Helmholtz Centers	3	6	8	9	4	7
Other	8	12	12	25	5	15
Fundamental research institutes[2]	–	–	*44*	*54*	*16*	*23*
Use-inspired basic research inst.[2]	*55*	*73*	*55*	*73*	*36*	*60*
Applied research institutes[2]	*14*	*23*	*12*	*22*	*6*	*9*
Total	**102**	**144**	**131**	**195**	**120**	**251**

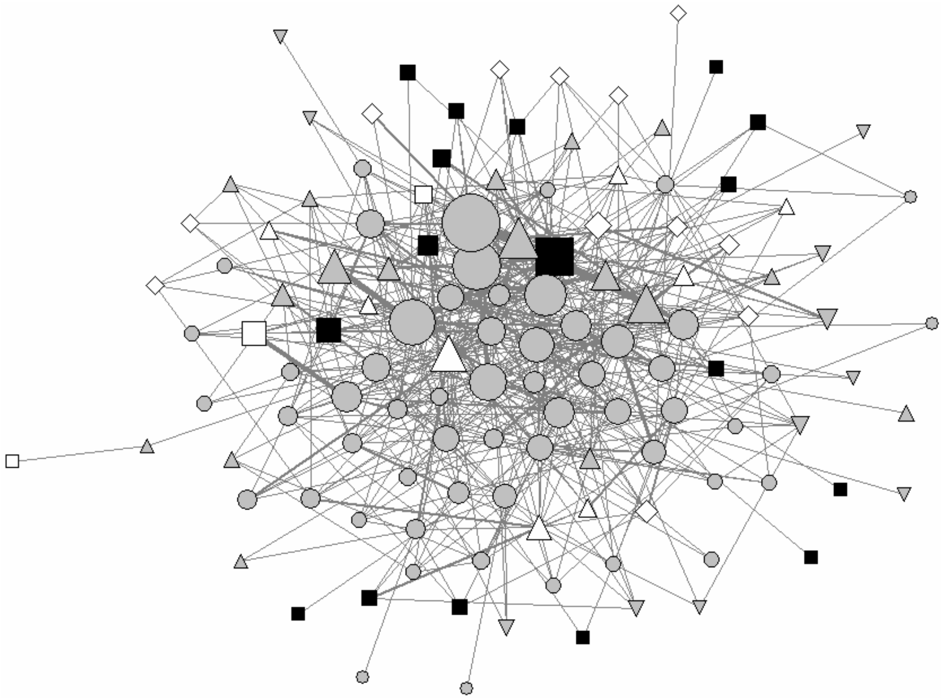
Source: Heinze (2006); [1] derived by NACE company codes; [2] derived by an indicator that measures volumes of applied research projects at national and EU level relative to the number of SCI publications. Due to missing data, some sub-categories do not add up to total number.

3.2 Co-publication Network

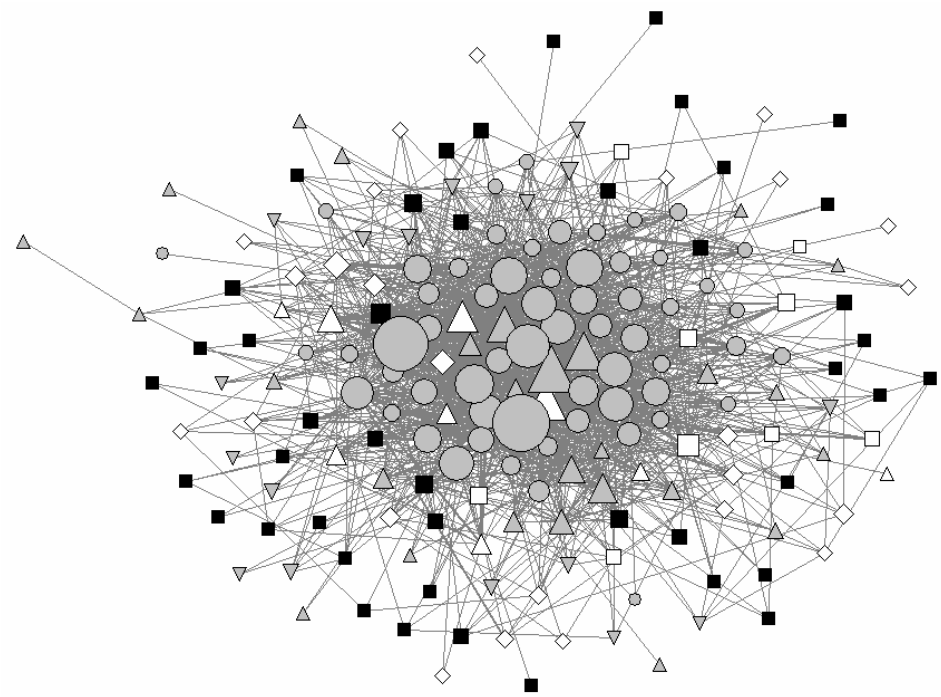
An important momentum of the development of the nano S&T field is its research base. Figure 4 shows the development of the German co-publication network from the period 1991-1995 to 1996-2000. The visualisation illustrates both a substantial increase in publication activity and a strengthening of the core-periphery structure. Firstly, the number of companies involved increases from 20 to 45, and public research units from 111 to 150, mostly institutes from the extra-university sector (Table 1). Secondly, collaboration intensifies as indicated by stronger ties. Most conspicuously, three major companies are situated in the network core in 1991-1995 (IBM, Siemens, BASF), whereas nearly all companies are in the periphery in 1996-2000. In contrast, a considerable number of Max Planck Institutes, the majority of which conduct fundamental research, move into the network core in the second half of the 1990s. We observe an interesting change with regard to the institutional base of nano S&T research. While large companies contributed substantially to publications at an early stage of field development, the public research sector takes over as the field matures. Today, universities, but increasingly also the extra-university institutes, are major actors in producing scientific findings in the nano S&T field.

Figure 4: Co-publication Network in Nano S&T, Germany 1991-2000

1991-1995



1996-2000



Source: Heinze (2006). Graph displays largest component. Layout using Netdraw®: node position via spring embedding algorithm (geodesic distances and node repulsion); node size: degree centrality (normalised); tie strength (normalised); companies: black boxes; universities: grey circles; Max Planck Institutes: grey upside triangle; Fraunhofer Institutes: grey downside triangle; Leibniz Institutes: white squares; Helmholtz Centers: white upside triangles; other research institutes: white rhombuses.

3.3 Co-patent Network

In chapter 2, we concluded from Figure 2 that there is substantial knowledge transfer between the public research sector and the private companies. In order to investigate the movement of knowledge and ideas adequately, we now analyse the co-patent network. Patents are a good proxy for technology development, particularly in science-based fields of technology (Meyer-Krahmer/Schmoch 1998). The analysis of the co-patent network is based on an important methodological consideration: the majority of patent applications in nano S&T are filed by companies in Germany, although we find an increasing number also from the extra-university research institutions which run dedicated patent offices, such as Garching Innovation, a company owned by the Max Planck Society (Noyons et al. 2003). However, collaborative activities between companies and research institutes seldom lead to patent applications where both legal entities apply for shared property rights. If public researchers are involved in a patent filed by a company, they usually appear only as inventors (with their private address). In order to fully capture public sector involvement in patenting, we matched inventor names with SCI authors, a method that significantly increased the number of research institutes in the patent database (Heinze 2006: 142-81). Consequently, co-patents between companies and public sector research units are in most cases applicant-inventor relations.

3.3.1 Meso Level Structure

While the predominant pattern in the co-publication network is a core-periphery structure that becomes more manifest over time, there is no such structure in the co-patent network.[14] Therefore, we investigate the *meso level of the co-patent network* by further differentiating among actor types. H1 draws on two important ideas from innovation studies: the concept of science-based companies with absorptive capacities for extra-mural knowledge production on the one hand, and the concept of use-inspired basic research as the predominant type of research in science-based fields of technology, on the other hand.

Hypothesis 1:
High-technology companies and use-inspired basic research institutes collaborate intensely in the development of new nanotechnologies.

The concept of science-based companies originates from the finding that in certain industrial sectors companies need access to extra-mural knowledge production, most importantly via cooperation with other companies, but also public research institutes, in order to stay competitive. Such companies dispose of *search and evaluation routines* that help them identify and absorb new external technological knowledge (Nelson 1995; Cohen/Levinthal 1990; Nelson/Winter 1982). While classical studies point to the chemical and the electronics industry (Pavitt 1984), more recent studies presented considerable evidence for the biotechnology industry in this regard (Gittelmann 2000; Liebeskind et al. 1996; Powell et al. 1996; Owen-Smith et al. 2002). Likewise, taxonomies were developed that measure the share

14 Visualisations of the co-patent network over the years 1991-2000 are published in Heinze (2006: 194-195).

of R&D investment relative to company turnover to distinguish between high-tech and low-tech firms (OECD 2001).

The concept of use-inspired research was introduced by Stokes (1997) to account for research that is neither purely fundamental nor fully applied. This influential distinction in STI studies was found particularly useful to capture the various types of research in science-based technologies, such as biotechnology (Evans 2004). We argue that Stokes' distinction is also useful to characterise research in the nano S&T field. Several interviews conducted by the author with university scientists from various disciplines and industrial researchers suggest that the study of fundamental nano-scale phenomena often implies technological aspects, although neither pure fundamental nor pure applied research have disappeared as legitimate ways of approaching new scientific questions.[15] We apply Stokes' three quadrant concept to differentiate among groups of research organisations. The three quadrants are operationalised by measuring the ratio of applied research activities relative to fundamental science at the organisational level for all German research units active in nano S&T between 1991-2000. Table 1 presents the distribution of both high-tech and low-tech companies, and the three Stokes types of research institutes.[16]

The question of interaction patterns between companies and research institutes can be linked to organisational routines, if the concept of *search and evaluation routines is extended* to research organisations. H1 claims that high-tech companies interact most intensely with those public research units that combine both fundamental and applied research questions in their activities. The crucial link is a common interest in research problems related to advance technological knowledge. Therefore, openness towards applied research is a necessary condition for high-tech companies and researchers in universities and other public sector institutes to get in touch. However, the companies' engagement is preconditioned on public researchers' superior scientific performance, on skills which companies cannot afford to maintain themselves in their day-to-day business. Consequently, H1 conjectures that there is a *proper blend* between institutional heterogeneity (the worlds of science and business) and similarity (common interest in technology development) that drives public-private research collaboration in nano S&T. It is noteworthy in this regard that studies on biotechnology typically dealt with company networks, but not inter-organisational networks between public research and private companies (Powell et al. 1996; Stuart/Podolny 1999; Ahuja 2000).

We test H1 by comparing tie densities between the five organisational categories. Densities are a convenient operationalisation of interaction intensities. As H1 expects a high propensity for interaction between high-tech companies and use-inspired basic research institutes, densities between these organisations should be considerably higher than for other dyadic relationships. Dyadic densities measure the ratio between factual ties (as observed in the co-patent network) and potential ties (derived from the number of organisations), as illustrated by

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15 Jansen (1995) discusses the tension between fundamental and applied research in high temperature superconductor technology field.

16 For methodical details, see Heinze (2006: 154-161).

the following examples. In 1991–1995, the sample contains 27 high-tech companies and 16 use-inspired basic research institutes, with 432 potential symmetric ties: 27 x 16 = 432. 12 factual ties are observed, therefore the density is 0.0278, which means that 2.8 percent of all potential ties materialised in the network. In 1996–2000 there are 65 high-tech companies and 23 use-inspired basic research institutes. 14 of the 1,495 (= 65 x 23) potential ties are present in the network, resulting in a density of 0.0094. The density of the full co-patent network in the first time period is 208/7140 = 0.0291, in the second period 324/31375 = 0.0103. Hence, the density of the co-patent network in 1996-2000 is three times lower than in 1991-1995 due to the expansion of the sample size. Single dyadic densities need to be interpreted against these overall network densities (Table 2).

The findings give strong empirical support to H1. A systematic comparison of all dyadic densities in the co-patent network over the time span 1991-2000 shows that high-tech companies are most densely connected to use-inspired basic institutes (Table 2). We also find quite strong relationships between high-tech companies and applied institutes, but much smaller values for fundamental research units. Consequently, the most interesting partners for companies are those research institutes which display scientific strength, but are still involved to a certain extent in technological problem-solving. This interpretation is corroborated by the high publication record of the respective institutes. Note that while the total co-patent network's density decreases by a factor three between the two time periods, dyadic densities between low-tech companies and fundamental institutes fall by a factor seven. Thus, the latter segment shows the strongest disintegration, while the relational density between high-tech companies and the applied institutes decreases by a factor two to two point five.

Table 2 shows the relational densities for the co-patent networks (above diagonal) and the co-publication networks (below diagonal). The results are similar. In the publication network, dyadic densities between high-tech companies and use-inspired basic institutes are also much higher than with either of the other two types of institutes. In addition, there is a company preference to co-author papers with fundamental institutes at an early stage of field development (0.0303 compared to 0.0167). In the latter half of the 1990s, however, this preference is reversed (0.0167 compared to 0.0220). Within the research sector, we also find a conspicuously strong interaction, with highest co-publication densities for the use-inspired institutes and their fundamental and application oriented neighbours. Complementarily, use-inspired institutes cooperate more actively with applied institutes in the co-patent network. Therefore, they are much better connected to either side, firstly to the fundamental institutes via co-publication ties, secondly to the applied institutes via co-patent ties. This fact, we assume, is another explanation why companies choose to interact with use-inspired basic institutes more often than with either of the two other institute types.

The findings in Table 2 refer to dyadic relationships. We also investigated if these results hold for tie relations of a higher order, such as clique formations. The clear answer is yes. The number of maximally connected subgroups (= cliques) in the co-patent network (mostly of size N = 3, 4) linking high-tech companies and use-inspired basic institutes expands over the

10-year period. Consequently, there is not only quantitative evidence in support of H1, but also structural evidence.[17]

Table 2: Densities in Nano S&T Co-patent and Co-publication Networks, 1991-2000

	Fundamental research institutes	Use-inspired basic research institutes	Applied research institutes	High-tech companies	Low-tech companies	Missing values
Fundamental research institutes		0,0591 0,0799	0,0189 0,0227	0,0303 0,0167	0,0000 0,0062	0,0000 0,0103
Use-inspired basic research institutes	0,0382 0,0087		0,0697 0,0971	0,0667 0,0698	0,0364 0,0434	0,0545 0,0289
Applied research institutes	0,0000 0,0145	0,0463 0,0296		0,0167 0,0220	0,0000 0,0000	0,0000 0,0152
High-tech companies	0,0278 0,0094	0,0669 0,0318	0,0494 0,0188		0,0167 0,0054	0,0000 0,0072
Low-tech companies	0,0089 0,0013	0,0179 0,0098	0,0119 0,0163	0,0053 0,0014		0,0000 0,0000
Missing values	0,0179 0,0022	0,0251 0,0114	0,0000 0,0111	0,0053 0,0005	0,0000 0,0005	

Source: Heinze (2006). First value: 1991-1995; second value: 1996-2000. Co-patent density: below diagonal. 1991-1995: 0,0291 [=208 factual ties/(120*119/2) potential ties]; 1996-2000: 0,0103 [=324 factual ties /(251*250/2) potential ties]. Co-publication density: above diagonal. 1991-1995: 0,0646 [=550 factual ties/(131*130/2) potential ties]; 1996-2000: 0,0826 [=1.536 factual ties/(195*194/2) potential ties].

3.3.2 Micro Level Structure

Nano S&T is a thriving field, as manifested in the increasing number of universities, research institutes and companies that entered the field during the period of 1991 and 2000 (Table 1). New topics create ample opportunities to link up with new extra-mural research units. However, interviews conducted by the author with managers in the chemical industry and administrators from the German Engineering Association suggest that there is strong competition between firms for access to top nano S&T scientists and groups. Although there is considerable thematic variability, and despite the growing number of public researchers entering the field, excellent research groups are in short supply. Hence, respondents argued that multiple company–multiple research institute cooperations are a common model. Accordingly, H2 claims that because competencies in nano S&T are distributed among a wide range of research institutes, companies cooperate not just with one but several universities and other public institutes in order to gain access to the latest advances and research frontiers.

Hypothesis 2:
Companies typically cooperate with several public sector research units to enhance their knowledge base.

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17 For further details, see Heinze (2006: 196-201).

We test H2 with a *block model analysis* that does not only identify subgroups in a network, such as cliques, but clusters actors with similar tie patterns that are not mutually connected to each other. Block model algorithms search for actors with equivalent or highly similar external relations by partitioning the matrix into blocks. Each block contains actors that are (ideally) equivalently positioned to other actors in the network (Wasserman/Faust 1999: 394-424; 681-684). Using the *tabu search algorithm* in Ucinet 6.0 (Borgatti et al. 2002), we iterate the calculation until a local optimum is reached using QAP correlation as validity criterion (Glover 1989; 1990). For both time periods, co-patent networks are partitioned by the algorithm into a similar number of blocks, 14 blocks in 1991-1995, 16 blocks in 1996-2000. Figure 5 shows relevant extracts from both co-patent networks.

The findings give partial support to H2, but additions and qualifications are necessary. In the first half of the 1990s, three types of blocks are detected:

- company blocks – No. III, X and XI;
- public sector research institute blocks (research blocks) – No. II, IV, V, VIII and XII;
- mixed blocks, embracing research institutes and companies – No. I, VI, VII and IX.

One of the research blocks, which is a subgroup but not a clique, embraces the Max Planck Institute for Polymer Research in Mainz, the University of Munster und the Technical Universities of Karlsruhe and Aachen. This subgroup has strong ties to Aventis (pharmaceutical company) and BASF (chemical company), both of which are company blocks (No. X, XI). A similar pattern is observed for the University of Heidelberg (No. IV) with ties to Bayer and BASF. In contrast, mixed blocks are often clique formations, where one high-tech company is connected with two application-oriented institutes.[18] In block VI we find Wacker Siltronic (chemical company), the University of Munich, and Max Planck Institute for Biochemistry in Munich; in block VII there is Bosch (electronics/mechanical engineering company) together with the Max Planck Institute for Solid State Physics in Stuttgart and the Leibniz Institute for New Materials in Saarbrucken.

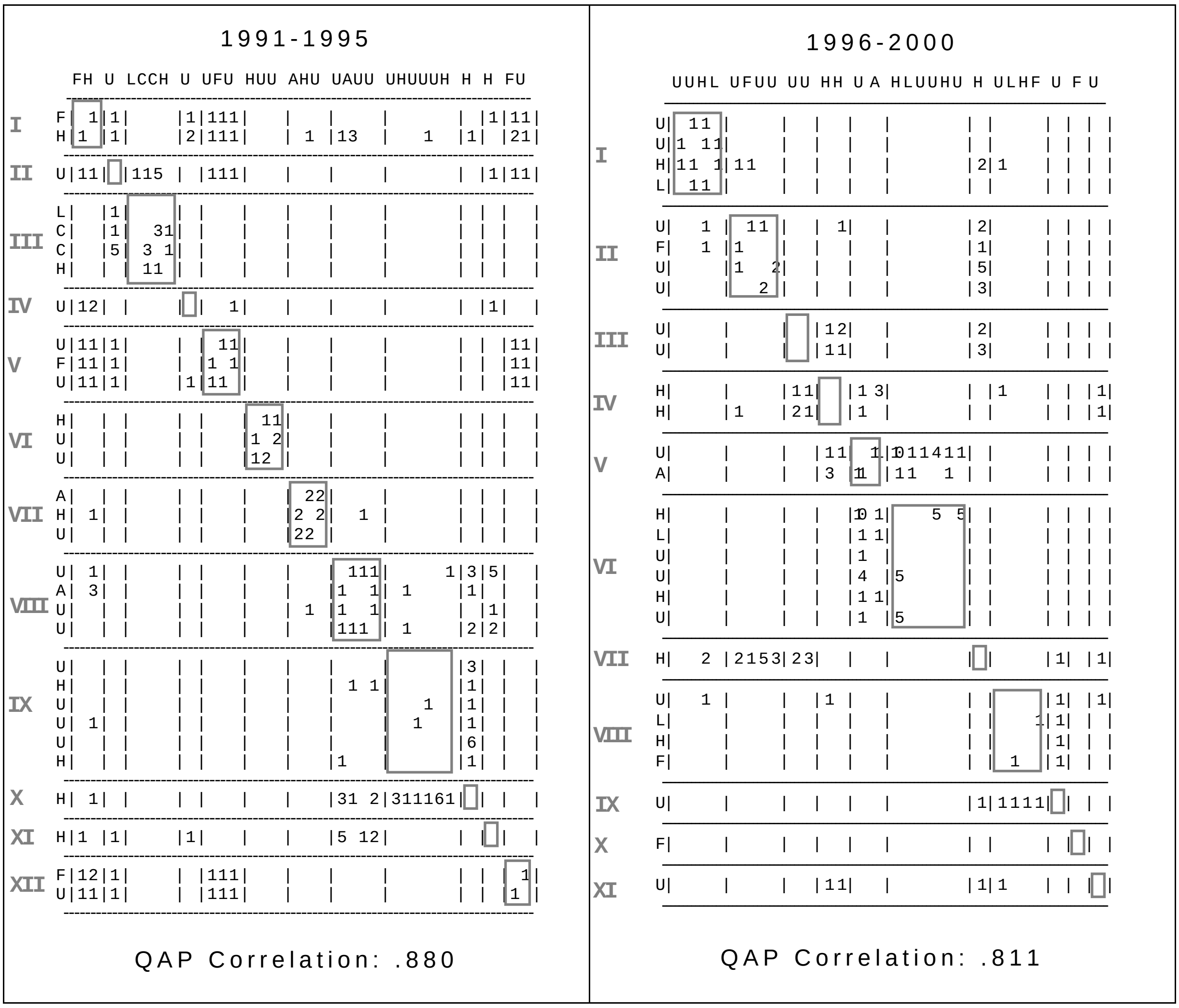
While many clique-like mixed blocks show strong internal collaboration and have few external ties, research blocks and company blocks typically have stronger external connections, but are only weakly integrated internally. This means that there are two conspicuous micro patterns in the co-patent network. The first pattern shows strong mutual ties between companies and public research institutes that tend to be exclusive, since these subgroups have sporadic external relations to other organisations only. Here, the fact that clique-like relationships are much stronger than external ties contradicts H2. The second pattern supports H2 and shows that companies compete for research organisations which, in turn, collaborate with more than one firm.

The same two patterns are also present in the second half of the 1990s (Figure 5). For instance, we find a mixed block including Siemens (electronics company), Vacuumschmelze (metal-processing company), the Max Planck Institute for Biochemistry in Munich and

[18] Either use-inspired basic research or pure applied research, see Figure 5.

University of Stuttgart (No. I) with only few external ties. Furthermore, we identify a research block (No. II) where two universities, namely the University of Freiburg and the University of Munster, collaborate with Bayer, BASF (chemical companies) and Infineon (semi-conductor company), but not among themselves. A check in the co-publication network shows that both universities have no co-authored papers either. Finally, some actors change their position over time. While the Leibniz Institute for New Materials in Saarbrucken is part of a clique-like mixed block in 1991-1995, it belongs to a densely connected research block in 1996-2000 (No. V) that does not have exclusive ties to one company, but several such relationships including Bayer, BASF, Henkel (all chemical companies) and Bosch (electronics/mechanical engineering company) in block no. IV and VI.

Figure 5: Block Model Solution for Nano S&T Co-patent Network, 1991-2000



Source: Heinze (2006). Figure shows matrix extracts from co-patent network in 1991-1995 and 1996-2000. Both matrices are symmetric and contain value data. Blocks and block numbers are indicated in grey color. Organisational abbreviations are: F = Fundamental research organisation; U = Use-inspired basic research organisation; A = Applied research organisation; H = High-tech companies; L = Low-tech companies; C = Company, missing value for High-tech/Low-tech.

One may ask for explanations of these two micro patterns in the German nano S&T co-patent network. Darby and Zucker argue that nanotechnology start-up companies in the US are founded around star scientists: „firms enter nanotechnology near where top scientists are making breakthrough discoveries and where skill levels in the work force are high“ (Darby/Zucker 2003: 22). Yet an analysis of the degree centrality of all research institutes in the co-publication network, an operationalisation of scientific visibility, only partially explains why we find either exclusive company–institute relations or the more competitive multiple companies–multiple institute model. Public institutes in mixed, exclusive blocks have much higher centrality scores in the co-publication network than research blocks embracing multiple public institutes. Some companies are apparently successful in establishing almost exclusive ties with highly central public research institutes. However, this is not always the case, since there are numerable single university research blocks that have similarly high centrality scores, but ties with several companies.

In contrast to Darby and Zucker’s findings for the US, in Germany there is neither an obvious regional distribution, nor do start-up companies play a significant role in the two micro patterns. Although the sample includes 16 start-up companies in 1996-2000 (which are younger than five years), they are all partitioned into the biggest, amorphous block which is not displayed in Figure 5. Likewise, while one of the mixed groups in 1991-1995 is clustered around Munich, other groups are extended across southern Germany. In sum, scientific visibility seems important for company decisions to form ties with public research institutions, but there is no clear correlation between either regional proximity or market entry and the two micro patterns identified by the block model analysis.

4 Network Position and Company Performance

There is abundant empirical evidence on the positive correlation between collaborative inter-organisational ties and company performance measures. Most studies have dealt with company networks, but did not investigate inter-organisational relations between public research and private companies (Stuart/Podolny 1999; Powell et al. 1999; Ahuja 2000). We derive hypotheses from this literature to test the effect of research-industry ties on the technological performance of companies.

Stuart/Podolny (1999) demonstrate that technology alliances in the semiconductor industry account for increasing company patent output in a 10-year time period. The more companies are embedded in corporate alliances, the more successfully they absorb external knowledge and exploit it technologically. Likewise, Ahuja (2000) finds evidence for a positive network effect on the technological performance of chemical companies for a 10-year time period. Furthermore, Powell et al. have shown for a large sample of biotechnology companies that collaborative activities increase network experience and capabilities to establish new and broader ties that, in turn, increase both visibility in the network and company growth. For a 10-year time window, they test the interaction effect between dependent variables (e.g. company growth) and independent variables (e.g. network centrality score) and were able to identify causal effects between the number and breadth of collaborative ties and performance measures (Powell et al. 1996; Powell 1998; Powell et al. 1999). They conclude that „a network of collaborative ventures serves as a locus of innovation because it provides fast access to knowledge and resources that are otherwise unavailable, while also testing internal expertise and learning capabilities“ (Powell 1998: 208).

We select three hypotheses from this literature which seem particularly relevant for the nano S&T field. H3 claims that the number of collaborative ties with public research institutes explains company's technological performance. The dependent variable is measured by the natural logarithm of patent applications in two time periods, 1991-1995 and 1996-2000, while the independent variables consist of three types of ties: co-patent relations, co-publications and collaborative applied research projects. In the multivariate regression models, we control for company size and R&D intensity.

Hypothesis 3:
Technological company performance increases with the number of collaborative ties to public sector research units.

H4 qualifies H3 in that it relates breadth of collaborative ties with company performance. We conjecture that companies file more patent applications if they succeed to establish broad communication channels to public sector institutes. For instance, co-publications represent fundamental science communication, while co-projects stand for applied technological aspects of collaborative research. The independent variable ranges from zero to four, indicating the number of communication channels between companies and public research institutes.

Hypothesis 4:
Technological company performance increases with bandwidth of collaborative ties.

H5 also qualifies H3 in that it links scientific visibility of collaboration partners with company performance. H5 conjectures that universities and extra-university research institutions with high degree centrality in the co-publication network have access to richer and many-faceted information and, thus, allow companies to arrive faster at patentable technological solutions. Companies with access to central actors in the scientific world should be more successful in the technological race than competitors without such ties.

Hypothesis 5:
Technological company performance increases with the number of collaborative co-patent ties to highly central public research units in the co-publication network.

Hypotheses H3 – H5 receive strong support by bivariate correlation analysis (Table 3). The number of firms' patent applications clearly increases with the number of ties to public research institutions in both time periods. But while the effects for co-patent and co-publication ties are comparably strong and stable, (r_{copat} = .627/.590; r_{copub} = .468/.498), the collaborative applied project tie effect is weaker and decreases over time (r_{coproj} = .390/.205). The strong co-patent and co-publication effects suggest that it makes a difference whether or not companies interact with public research in the process of developing new nanotechnologies, and that they benefit considerably from the science base of their collaborators. This effect is particularly strong both for companies that collaborate with highly central universities and other public institutes (although this effect decreases over time: $r_{high\ centr.}$= .548/.391), and companies that manage to build up multiple types of relationships into the world of science ($r_{bandwidth}$= .662/.536).

Support for H3 – H5 is also remarkably robust when using multivariate regression techniques, although some of the bivariate conclusions require qualification. Since the dependent variable shows a negative binomial distribution, we run respective regression models using STATA (Table 4). We control for effects in the independent variables over time by introducing three additional variables (number of publications, patents and projects, respectively), and we use residual values for the collaboration variables in the second time period. Residual values mean that we only retain the value fraction (of 1996-2000) which cannot be explained by the variables of the preceding period (1991-1995). Table 4 does not report panel regression results, a procedure that is not suited to our data set, but compares results from two cross-sectional regression analyses.

H3 is strongly confirmed for co-patent ties, and fairly supported for co-publication ties across the 10-year period, but clearly rejected for co-project ties. The bandwidth variable (H4) absorbs the co-publication effect when introduced to the analysis (model 2). Centrality in the co-publication network qualifies the co-publication effect only in 1996-2000 (H5), while it has no effect in 1991-1995. Since the bandwidth variable absorbs the centrality variable's explanatory power, it is the most important independent variable (model 4). Note that at an early stage of nano S&T field formation, all reported effects pertain especially to large incumbent companies, whereas the effect gets small and insignificant when new start-up firms enter the field in 1996-2000.

Table 3: Bivariate Correlations, 1991-2000

		1	2	3	4	5	6	7	8	9	10	11
1	Number patents (ln)											
2	High-tech companies (dummy)	,278*										
		,298***										
3	Large companies (dummy)	,339**	,314*									
		,322***	,370***									
4	Number patents 1991–1995											
		,472***	,219**	,275**								
5	Number publications 1991–1995											
		,524***	,162*	,308***	,594***							
6	Number collaborative projects 1991–1995											
		,357***	,238**	,210**	,312***	,604***						
7	Number co-patent ties with research institutes	,627***	,279*	,022								
		,590***	,139	,123	,010	,154	-,005					
8	Number co-project ties with research institutes	,390**	,260*	,227				,409**				
		,205*	,122	,031	,097	,114	,137	,227**				
9	Number co-publication ties with research institutes	,498***	,318*	,080				,317*	,288*			
		,468***	,345***	,329***	,311***	,306***	,337***	,170*	,266**			
10	Tie bandwidth	,662***	,476***	,259*				,472***	,464***	,547***		
		,536***	,261**	,253**	,378***	,441***	,392***	,277***	,358***	,587***		
11	Number co-patent ties with highly central research inst. in co-publication network	,548***	,312*	,157				,366**	,104	,164	,555***	
		,391***	,175*	,143	,108	,183	,151	,256**	,089	,177*	,366***	

Source: Heinze (2006); * p < .05, ** p < .01, *** p < .001. First value: 1991-1995 (N = 62); second value: 1996-2000 (N = 155); control variables 4 – 6 only for 1996-2000.

Interviews conducted by the author corroborate and further qualify the regression results. Experts argued that measuring applied collaborative research via national and EU level projects will not display the whole spectrum of collaboration between industry and academia. Hence, insignificant effects in the multivariate regression models might be caused by the indicator’s incompleteness. With respect to the co-publication and co-patent effects, interviewees generally agreed that nano S&T companies are dependent on the public research base, and even maintained that technological progress would be much slower if such collaborations would not take shape. Some interviewees voiced criticism of the common strategy of large companies to reduce their exploratory research and to outsource research capabilities to the public sector. Consider one of such comments by a scientist working in an extra-university research centre:

> „Companies conduct collaborative research very efficiently. Cooperations with universities and extra-university research institutes just increase their output. Because they are not going to do these things by themselves. BASF has, I think, thousands of collaborative contracts with universities and extra-university institutes. The former central research division was cut down in small single units which are very efficient today, in the sense that they are looking, who has this and that competence, and then try to get projects started. You are just faster when a professor and his doctoral students think about a problem time and again“ (translation by author).

Table 4: Negative Binomial Regression of Company Patent Output (ln), 1991-2000

	Model 1		Model 2		Model 3		Model 4	
	1991-1995	1996-2000	1991-1995	1996-2000	1991-1995	1996-2000	1991-1995	1996-2000
Constant	-1,286***	-,899***	-2,027***	-1,926***	-1,911***	-1,324***	-3,248***	-1,866***
	(,257)	(,129)	(,443)	(,306)	(,453)	(,221)	(,766)	(,309)
Number patents				,023		,038		,025
1991–1995				(,022)		(,023)		(,023)
Number collaborative projects				,028		,056		,032
1991–1995				(,051)		(,050)		(,051)
Number publications				,004		,016		,005
1991–1995				(,022)		(,022)		(,022)
Number co-patent ties with	,469***	,106***	,369**	,093***	,431*	,091***	,490**	,092***
research institutes	,123)	(,017)	,135)	(,019)	(,173)	,020)	(,164)	(,020)
Number co-project ties with	,003	-,016	-,041	-,036	-,018	-,007	-,075	-,032
research institutes	(,025)	(,040)	(,029)	(,039)	(,034)	(,039)	(,040)	(,039)
Number co-publication ties with	,055***	,139***	,032	,000	,087**	,071*	,002	,007
research institutes	(,024)	(,029)	(,036)	(,044)	(,033)	(,036)	(,042)	(,044)
Tie bandwidth			,985**	,578**			1,433*	,501**
			,378)	(,167)			,553)	(,178)
Number co-patent ties with					-,015	,010**	-,025	,006
highly central research institutes in co-publication network					(,015)	(,003)	,020)	(,004)
High-tech companies (dummy)			-1,193	,201	-,393	,147	-1,329	,142
			(,702)	(,303)	(,522)	(,310)	,730)	(,308)
Large companies (dummy)			1,044*	,247	1,243*	,292	1,120*	,264
			(,485)	(,300)	(,512)	(,298)	(,525)	(,296)
Number of observations (N)	62	155	62	155	62	155	62	155
Variance explained (Pseudo-R2)	,190	,143	,347	,249	,289	,230	,360	,256
Degrees of freedom (df)	59	152	56	146	56	146	55	145

Source: Heinze (2006); * p < .05, ** p < .01, *** p < .001; Standard errors in parentheses; control variables 1 – 3 only for 1996-2000; variables 4 – 6 are residual values in 1996-2000.

5 Discussion

The emergence of the nano S&T field is rooted in a number of research breakthroughs in applied physics (e.g. STM/AFM), macromolecular chemistry (e.g. fullerenes), and more recently in electronics (e.g. nano transistor). New journals were established, university courses and degrees have been set up, and the number of conferences and workshops on nano scale phenomena increased exponentially in recent years. In the early 1990s, the field received considerable attention from policymakers who have channelled substantial resources into the field since. Nano S&T is not a coherent field, but embraces an enormous thematic breadth and cuts across established disciplinary and sectoral boundaries. Most importantly, nano S&T is a science-based field, where technological innovation builds on progress in the research sector.

To understand the knowledge transfer between companies and public research institutions adequately, we mapped a complete multi-dimensional inter-organisational network of German companies, universities and other public research institutions covering the years 1991-2000. We demonstrate that the co-publication network has developed a core-periphery structure over time, in which some companies were key players at an early stage of field formation, but that later universities and other extra-university institutes (e.g. Max Planck Institutes) are the predominant drivers of scientific progress. In contrast, the co-patent network is structured differently. Our hypothesis is confirmed that interaction between high-technology firms and use-inspired research institutes contributes most to the development of the field. While the majority of these firms are incumbents, new companies entered the field in the second half of the 1990s. Furthermore, while many companies interact with several universities or other public institutes, some succeed in establishing almost exclusive relationships with public research units. Ar set of hypotheses investigates the network effects of colllaborative ties on company performance in more detail. We find that both co-patent and co-publication ties are most consequential in strengthening technological capabilities of firms, that multiple interaction channels increase company performance, and that companies profit most from collaborating with scientifically central universities and institutes.

For describing and analysing the formation of new science-based fields of technologies, it is essential to understand the interface between different institutional settings, such as companies and public research institutions. Network analyses are a powerful tool to yield both descriptive but also analytical insights in the interaction of the science system and the economic system. Nano S&T has opened up new "territory" for many established companies, universities and other public research institutes to interact, as evident from the growth of the organisational field and the network data. Our analysis successfully linked findings from network analysis to technological capabilities of firms by using relatively straightforward indicators and statistical tools. This *knowledge and technology transfer* perspective is important for STI policy, and it has been influential in the current literature on technological innovation (Cohen et al. 2003; Edquist 1997; Nelson/Nelson 2002).

In contrast, we know little about the consequences of industrial partnerships on the quality of public science. As was shown for nano S&T in this article, companies' technological competitiveness depends on the science base in the public research sector. Since inter-organisational relations spanning the science system and the economic system are an important momentum of the development of science-based technologies, one should also examine the consequences of such network ties on creativity and path-opening research in the sciences.

In a recent longitudinal study on a subfield of biotechnology, Evans (2004) demonstrates that novelty and persistence of researchers and public research organisations decrease if they interact continuously with industry. Evans argues that “on average, industrial partnerships make science less novel and more commercial; they influence scientists to be less persistent in their inquiry and less apt to share research with their colleagues. (…) Across the entire web of connected ideas, phenomena and methods that constitutes the frontier of science, industrial partnerships influence the topics they sponsor to become less focal in this web” (Evans 2004: 6). Most interestingly, the author evinces that while elite institutions have greater bargaining power when negotiating collaborative relations with industry, the bulk of research institutions tends to become extended work-benches for firms: “Central, high status PIs [Principal investigators, T.H.] and research organizations use industry ties to support their science with no harmful effects to the academic quality of their science, while the novelty and persistence of research produced by researchers in less central positions erodes with industrial collaboration. (…) Central actors have greater bargaining power to „cut better deals“ in their negotiation of industry collaborations” (Evans 2004: 106).

Evans’ results indicate that relationships between the private company sector and the public research sector can indeed become too close with harmful consequences for both, because if the web of science is stretched thin, the basis for subsequent technological innovations becomes fragile. The capabilities of the public research sector to produce a continuous stream of cognitive innovations need to be analysed in more empirical depth. Evans’ analyses are an interesting starting point for other science-based fields, but particularly for the field of nano S&T which is about two decades younger than biotechnology. Therefore, we suggest combining the existing *technology transfer perspective* and a dedicated *sociology of science perspective* when exploring field maturation in nano S&T.

References

Ahuja, G. (2000): Collaboration networks, structural holes, and innovation: A longitudinal study, in: Administrative Science Quarterly 45, 425–55.

Bachmann, G. (1998): Innovationsschub aus dem Nanokosmos, Düsseldorf: VDI-Technologiezentrum.

Binnig, G.; Gerber, C.; Stoll E.; Albrecht, T. R.; Quate, C. (1987): Atomic Resolution with Atomic Force Microscope, in: Europhysics Letters 3 (12), 1281-1286.

Binnig, G.; Quate, C.; Gerber, C.; Weibel, E. (1986): Atomic Force Microscope, in: Physical Review Letters 56 (9), 930-933.

Binnig, G.; Rohrer, H. (1982b): Scanning Tunneling Microscopy, in: Helvetica Physica Acta 55 (6), 726-735.

Binnig, G.; Rohrer, H. (1982a): Scanning Tunneling Microscopy, in: Surface Science 126 (1-3), 336-344.

Borgatti, S.; Everett, M.; Freeman, L. (2002): Ucinet 6 for Windows. Software for Social Network Analysis, Natick: Analytic Technologies.

Burt, R. S. (2000): Decay Functions, in: Social Networks 22 (1), 28.

Burt, R. S. (2004): Structural holes and good ideas, in: American Journal of Sociology 110 (2), 349-399.

Carlsson, B. (Ed.) (2002): Technological Systems in the Bio Industries. An International Study, Dordrecht: Kluwer.

Cohen, W.; Levinthal, D. A. (1990): Absorptive capacity: A new perspective on learning and innovation, in: Administrative Science Quarterly 35, 128–52.

Cohen, W. M.; Nelson, R. R.; Walsh, J. P. (2003): Links and impacts: the influence of public research on industrial R&D, in: Geuna, A.; Salter, A. J.; Steinmueller, E. W. (Ed.): Science and Innovation: Rethinking the Rationales for Funding and Governance, Cheltenham, UK; Northhampton, MA, USA: Edward Elgar, 109-146.

Collier, C.; Wong, E.; Belohradsky, M.; Raymo, F.; Stoddart, J.; Kuekes, P.; Williams, R.; Heath, J. (1999): Electronically configurable molecular-based logic gates, in: Science 285 (5426), 391-394.

Darby, M. R.; Zucker, L. (2003): Grilichesian Breakthroughs: Inventions of methods of inventing and firm entry in nanotechnology, Cambridge, Massachusetts: NBER Working Paper 9825.

Edquist, C. (Ed.) (1997): Systems of Innovation. Technologies, Institutions and Organizations, London: Pinter.

Evans, J. A. (2004): Sharing the Harvest: The Uncertain Fruits of Public/Private Collaboration in Plant Biotechnology, Doctoral Dissertation, Department of Sociology, University of Stanford.

Feynman, R. (1960): There's plenty of room at the bottom, in: Engineering & Science 23 (5), 22–36.

Freeman, C. (1991): Networks of innovators: A synthesis of research issues, in: Research Policy 20, 499–514.

Gittelmann, M. (2000): Mapping National Knowledge Networks: Scientists, Firms, and Institutions in Biotechnology in the United States and France, Doctoral Dissertation, University of Pennsylvania.

Glover, F. (1989): Tabu Search – Part I, in: ORSA Journal on Computing 1 (3), 190–206.

Glover, F. (1990): Tabu Search – Part II, in: ORSA Journal on Computing 2 (1), 4–32.

Heath, J.; OBrien, S.; Zhang, Q.; Liu, Y.; Curl, R.; Kroto, H.; Tittel, F.; Smalley, R. (1985): Lanthanum complexes of spheroidal carbon shells, in: Journal of the American Chemical Society 107 (25), 7779-7780.

Heinze, T. (2004): Nanoscience and Nanotechnology in Europe: Analysis of Publications and Patent Applications including Comparisons with the United States, in: Nanotechnology Law & Business 1 (4), 427-447.

Heinze, T. (2005): Wissensbasierte Technologien, Organisationen und Netzwerke. Eine Untersuchung der Kopplung von Wissenschaft und Wirtschaft, in: Zeitschrift für Soziologie 34 (1), 62-80.

Heinze, T. (2006): Kopplung von Wissenschaft und Wirtschaft. Das Beispiel der Nanotechnologie, Frankfurt/New York: Campus (forthcoming).

Heinze, T.; Kuhlmann, S. (2006): Analysis of heterogeneous collaboration in the German research system with a focus on nanotechnology, in: Jansen, D. (Ed.): New Forms of Governance in Research Organizations. From Disciplinary Theories towards Interfaces and Integration, Heidelberg: Springer (forthcoming).

Hullmann, A. (2005): The European Action Plan on Nanotechnology, Presentation at the Workshop "Towards a European Digital Nanotechnology Library", 5 July 2005, Brussels.

Hullmann, A.; Meyer, M. (2003): Publications and patents in nanotechnology. An overview of previous studies and the state of the art, in: Scientometrics 58 (3), 507-27.

Iijima, S. (1991): Helical microtubules of graphitic carbon, in: Nature 354 (6348), 56-58.

Iijima, S.; Ajayan, P.; Ichihashi, T. (1992): Growth-model for carbon nanotubes, in: Physical Review Letters 69 (21), 3100-3103.

Jansen, D. (1995): Convergence of Basic and Applied Research? Research Orientations in German High-Temperature Superconductor Research, in: Science, Technology, and Human Values 20 (2), 197-233.

Kaufmann, A.; Tödtling, F. (2001): Science-industry interaction in the process of innovation: The importance of boundary-crossing between systems, in: Research Policy 30, 791–804.

Kroto, H.; Heath, J.; OBrien, S.; Curl, R.; Smalley, R. (1985): C-60 - Buchminsterfullerene, in: Nature 318 (6042), 162-163.

Liebeskind, J. P.; Oliver, A.; Zucker, L.; Brewer, M. (1996): Social networks, learning, and flexibility: Sourcing scientific knowledge in new biotechnology firms, in: Organization Science 7 (4), 428–43.

Luther, W.; Malanowski, N. (2004): Das wirtschaftliche Potenzial der Nanotechnologie, in: Technikfolgenabschätzung 13 (2), 26-33.

Malerba, F. (2000): Sectoral Systems in Europe – Innovation, Competitiveness and Growth (ESSY), in: Milano.

McPherson, M.; Smith Lovin, L.; Cook, J. (2001): Birds of a Feather: Homophily in Social Networks, in: Annual Review of Sociology 27, 415-444.

Meyer, M. (2001): Patent citation analysis in a novel field of technology: An exploration of nano-science and nano-technology, in: Scientometrics 51 (1), 163-183.

Meyer, M.; Persson, O. (1998): Nanotechnology - Interdisciplinary, Patterns of Collaboration and Differences in Application, in: Scientometrics 42 (2), 195-205.

Meyer-Krahmer, F.; Schmoch, U. (1998): Science-based technologies: University-industry interaction in four fields, in: Research Policy 27, 835–51.

Nelson, R. (1995): Recent evolutionary theorizing about economic change, in: Journal of Economic Literature 33, 48–90.

Nelson, R.; Nelson, K. (2002): Technology, institutions, and innovation systems, in: Research Policy 31, 265-272.

Nelson, R.; Winter, S. G. (1982): An evolutionary theory of economic change, Cambridge: Harvard University Press.

Noyons, E. C. M.; Buter, R.; Raan, A. F. J. v.; Schmoch, U.; Heinze, T.; Hinze, S.; Rangnow, R. (2003): Mapping Excellence in Science and Technology across Europe. Nanoscience and Nanotechnology, Report to the European Commission: University of Leiden.

OECD (Ed.) (2001): Science, Technology and Industry Scoreboard 2001: Towards a Knowledge-Based Economy, Paris: Organisation for Economic Co-operation and Development.

Owen-Smith, J.; Riccaboni, M.; Pammolli, F.; Powell, W. W. (2002): A comparison of U.S. and European university–industry relations in the life sciences, in: Management Science 48 (1), 24–43.

Pavitt, K. (1984): Sectoral patterns of technical change: Towards a taxonomy and a theory, in: Research Policy 13, 343-373.

Powell, W. W. (1998): Inter-organizational collaboration in the biotechnology industry, in: Journal of Institutional and Theoretical Economics 152, 197–215.

Powell, W. W.; Koput, K. W.; Smith-Doerr, L. (1996): Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology, in: Administrative Science Quarterly 41, 116–45.

Powell, W. W.; Koput, K. W.; Smith-Doerr, L.; Owen-Smith, J. (1999): Network position and firm performance: Organizational returns to collaboration in the biotechnology industry, in: Research in the Sociology of Organizations 16, 129–59.

Powell, W. W.; White, D. R.; Koput, K. W.; Owen-Smith, J. (2005): Network Dynamics and Field Evolution: The Growth of Interorganizational Collaboration in the Life Sciences, in: American Journal of Sociology 110 (4), 1132-1205.

Ratner, M.; Ratner, D. (2003): Nanotechnology. A Gentle Introduction to the Next Big Idea, New Jersey: Pearson Education.

Rieth, M. (2003): Nano-Engineering in Science and Technology. An Introduction to the World of Nano-Design, New Jersey: World Scientific.

Schmoch, U. (2003): Hochschulforschung und Industrieforschung. Perspektiven der Interaktion, Frankfurt am Main: Campus.

Scott, R. W.; Ruef, M.; Mendel, P. J.; Caronna, C. A. (2000): Institutional Change and Healthcare Organizations. From Professional Dominance to Managed Care, Chicago and London: Chicago University Press.

Stokes, D. E. (1997): Pasteur's Quadrant. Basic Science and Technological Innovation, Washington D.C.: Brookings Institution Press.

Stuart, T. E.; Podolny, J. M. (1999): Positional consequences of strategic alliances in the semiconductor industry, in: Research in the Sociology of Organizations 16, 161–82.

Tans, S.; Verschueren, A.; Dekker, C. (1998): Room-temperature transistor based on a single carbon nanotube, in: Nature 393 (6680), 49-52.

Thornton, P. (2004): Markets from Culture. Institutional Logics and Organizational Decisions in Higher Education Publishing, Stanford: Stanford University Press.

Valentín, E. M. M. (2002): Co-operative relationships. A theoretical review of co-operative relationships between firms and universities, in: Science and Public Policy 29, 37–46.

Wasserman, S.; Faust, K. (1999): Social Network Analysis: Methods and Applications, Cambridge, UK: Cambridge University Press.

Zucker, L.; Darby, M. R. (2005): Socio-economic impacts of nanoscale science: Initial results and Nanobank, Cambridge, Massachusetts: NBER Working Paper 11181.