Cross-Pollination in Science and Technology: Concept Mobility in the Nanobiotechnology Field

STINE GRODAL*
GRID THOMA**

* School of Management
Boston University
Boston, MA, 02215, USA
grodal@bu.edu[1]

** University of Camerino and
CESPRI, Bocconi University and
Milan, Italy
grid.thoma@unibocconi.it

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[1] Corresponding author

ABSTRACT

The emergence of new research based organizational fields drives both scientific progress and economic growth. The emergence of fields necessitates a movement of knowledge between participants within the field. However, little is known about the drivers and dynamics of knowledge diffusion within emerging fields. Research has shown that cross-pollination of knowledge plays an important role in innovative processes. However, these studies investigated cross-pollination at the team or individual level or through case-studies of individual technologies while assuming that cross-pollination occurred between concepts. In this paper we move the unit of analysis to the level of the individual concept, and investigate how the cross-pollination of concepts influences concept mobility. The paper, thus, extends the literature's consideration of the impact of cross-pollination on innovative outcomes to investigating how cross-pollination influences knowledge dynamics. Our setting is the cross-pollination of knowledge between nanotechnology and biotechnology, which yielded the new field nanobiotechnology. Drawing on a large dataset of publications, patents and press-releases between 1991 and 2005 we show that cross-pollination facilitates the mobility of concepts between science, technology and commercialization. Furthermore, the growth of the nanobio field exceeded the growth within both nanotechnology and biotechnology. Scientists who reside in commercial firms generally assist the mobility of concepts, but hinder the mobility of cross-pollinated concepts.

Keywords: technology; science; commercialization; cross-pollination

CONCEPT MOBILITY

The intersection of technological fields yields a fertile breading ground for new ideas (Fleming 2004; von Hippel 1988). Academic and industry scientists participate in the dissemination and commercialization of these new ideas thereby stimulating the creation of novel fields (Louis et al. 1989). A sign of the increasing importance of science in technological development is the sharp increase in the number and share of literature citations in patents (Narin and Olivastro 1992; Narin, Hamilton and Olivastro 1997), suggesting that inventors increasingly draw on inputs from published scientific research.

The key factor that science contributes to commercial production is knowledge. In the post-industrial society knowledge has become the principal asset in productions, hence the availability and skills to generate and integrate knowledge within the organization determines its economic value (Elliasson 1996). Frequently, it is the knowledge incorporated in the product and not the production costs that determines the market price of an object or a service (Ruttan 2001). There is disagreement within the literature about how to conceptualize and measure knowledge mobility. A large stream of literature has drawn on Polanyi's (1956) concept of tacit knowledge, i.e. that people know more than they can express in words. Zander and Kogut (1995) argue that firms know more than what is in their contracts and that technology transfer often requires the movement of tacit knowledge. Tacit knowledge defies explication, and therefore lacks a paper trail. Many studies have thus investigated other knowledge traces that can be captured quantitatively. Cohen and Levinthal (1990) argue that R&D spending serves as a proxy for the production of knowledge within a firm, but they do not measure knowledge mobility. Recently a stream of research has captured the mobility of knowledge by measuring citation patterns among both scientific articles and patents (Gittelman and Kogut 2001; Katila and Ahuja 2002). While moving closer to a quantitative measure of knowledge citations fall short of measuring knowledge directly, because a citation can have multiple meanings and refer to a wide spectrum of concepts and ideas within the article. To develop a more specific notion of knowledge dynamics we turn our focus to the mobility of individual concepts.

Concepts involved in the commercialization of knowledge exist in three integrated but separate institutional environments: science, technology and commerce. In science researchers generate scientific knowledge, which they disseminate through scientific articles, presentations at research conferences and their informal network of friends and colleagues. Some scientific concepts are translated into technological concepts in the form of technical drawings, documentation and patents. A fraction of these technological concepts are subsequently integrated into actual products; they are commercialized (Agrawal 2006). We define *science* based on its method of dissemination, i.e. science is the knowledge that is published in scientific articles, where it is made publicly available for others to read and use. *Technology* is technical knowledge disclosed by inventors in patent documents. An invention needs to be novel and useful in order to be patented, and the public description of the invention enables lawful enforcement of its claims.

While studies and surveys have suggested that most inventions are patented many scientific ideas still are not integrated into technologies (OECD 2007). Further, the literature often assumes that technological concepts and commercialization are identical phenomena, measured by whether a scientific concept is paralleled with a patent (Murray 2002). There is however evidence that even though a scientific concept is translated into a technological possibility in the form of a patent it is not always commercialized (Mirowski and Sent 2002). Research on the commercialization of knowledge has increased over the last decade, but we still lack an understanding of how and why some concepts move between knowledge spaces, but others fail to proliferate (Aldrich 1999).

Thus, the research question that we address in this paper is: *What are the drivers of concepts mobility between science, technology and commercialization?*

Cross-pollination

Studies of science and technology show that radical innovations spur the emergence of new fields (Basalla 1988). The development of genetic engineering, for example, enabled the emergence of the biotechnology industry (Powell, Koput and Smith-Doerr 1996; Zucker, Darby and Brewer 1998). Characteristic of most novel technological fields is that they proliferate at the periphery of existing technological fields cross-pollinating knowledge from separate technological areas (Hargadon and Sutton 1997; Hargadon 2003; von Hippel 1988). Cross-pollination is defined as the recombination of previously separate concepts**.** Biotechnology emerged at the intersection of biology and organic chemistry. The collaboration of people in multiple disciplines enabled the discovery of DNA as a double helix. Rosalind Franklin and her collaborator Maurice Wilkins were educated as chemists, James Watson had a degree in zoology, and Francis Crick had a degree in physics (Stokes 1982). The later development of molecular biology and its commercialization in the form of biotechnology drew attendance from people in chemistry, biology and physics. Digital sound, which emerged at the intersection between computer science and music, is another example of a new interdisciplinary field. It was only through the availability of persons with connections both within the computer science and the music department that the first digital synthesizer was developed. Digital sound is now a key element in the multibillion dollar music industry (Nelson 2005).

The existing research on cross-pollination has focused either on cross-pollination at the level of the individual, the team, or case studies of individual technologies (Fleming and Sorenson 2001; Hargadon and Sutton 1997; Schumpeter 1934). Schumpeter (1934) described the hallmark of entrepreneurship as recombining resources in novel ways. In Schumpeter’s account the locus of cross-pollination is with the individual entrepreneur, who recombines elements of her environment in novel ways. Padgett (2001) also embodies this perspective as he views entrepreneurs as recombining logics in the environment in order to create new organizational forms. Another line of research has emphasized the group as the unit of analysis. Fleming (2004) shows that interdisciplinary teams produce more radical innovations than disciplinary based teams. Hargadon and Sutton demonstrate the condition under which teams are more likely to generate cross-pollinated results. Further, in the video-game industry Tschang (2007) finds that creativity in game design studios occurs through recombination of elements from prior games. Yet another line of research focuses on cross-pollination within individual technologies by examining the knowledge flows that facilitated their creation (Brusoni, Prencipe and Pavitt 2001; Stankiewicz 2000). Common across these research streams is an implicit assumption that novel *concepts* are cross-pollinated. But the studies fail to examine cross-pollination at the level of the concept; instead they measure other proxies to assess whether cross-pollination has occurred.

Furthermore, the literature on cross-pollination has primarily been concerned with whether cross-pollination yields innovative outcomes (Flemming 2004). However, for cross-pollinated ideas to make an impact on technology and economic growth they need to move from their locus of first use to other institutional arenas. Otherwise the cross-pollinated concepts might be innovative, but they will never gain widespread acceptance. For example Schumpeter's theory of entreprenurship is based not only on the assumption that the entrepreneur recombines existing knowledge in the creation of novel concepts, but also that the novel concepts proliferate after cross-pollination has occurred (Schumpeter 1934). We thus hypothesize:

> *Hypothesis 1a(1b): Cross-pollination facilitates concept mobility from science (technology) to technology (commercialization)*

Proximity

For concepts to move from one sphere to the other they need to be translated and integrated to fit the social structures and prescriptions characteristic of the receiving sphere (Bechky 2003). The process of translating concepts between spheres is made easier if individuals involved in the translation process possess knowledge from both spheres (Bonaccorsi and Thoma 2007).

It has become increasing common for scientists and industrial researchers alike to participate in both research and commercialization efforts. University scientists not only publish their work, but also write patents to claim the commercialization rights of their discovery. In most technical fields the origin of entrepreneurship can be traced to academic scientists[2] (Klepper 2001; McKelvey 1996).

Furthermore, industrial scientists are no longer satisfied just commercializing their invention, but wish to publish their findings in academic journals (Colyvas and Powell 2006; Owen-Smith and Powell 2001). The multivocality of entrepreneurs facilitates the mobility of concepts between science and technology. In the process of science commercialization the availability of individuals who are familiar with both science and commerce facilitates the mobility of concepts from science to technology. We thus hypothesize:

> *H2a(h2b): Proximity to commerce facilitates concept mobility between science and technology (commercialization)*

The impact of commerce on science has been extensively debated in the literature (Dasgupta and David 1994). Some studies suggest that communication between industrial and academic scientists stimulates both scientific inventions and technological innovation. The argument draws on the observation that the nature of discovery is unpredictable and chaotic,

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[2] See research on biotechnology (McKelvey 1996; Orsenigo, Pammolli, Riccaboni 2001; Owen-Smith 2002; Zucker and Darby 1996), chemical and electrical engineering (Kenny and Goe 2004; Mowery and Rosenberg 1998), semiconductors and lasers (Klepper 2001).

and that interaction between institutions with different beliefs, goals and values can yield unexpected discoveries (Van de Ven et al. 1999). Other studies have questions the long term benefits of collaborations between academia and industry by pointing to the norms of secretiveness and proprietary views of knowledge prevalent among industry scientists. Close relationships between academia and industry might lead to a diffusion of industry practices to scientific institutions (Etzkowitz 1998). Furthermore, gifts provided to academic institutions from industry might come with non-disclosure agreements, demands to provide knowledge that is relevant for industry, and pressure to not publish unflattering research results (Etzkowitz and Leydesdorff 1995).

A central question in the debate has been the extent to which industrial scientists produce knowledge that is radically novel. Science and commerce differ to the extent that they value the exploration versus the exploitation of knowledge (Nowotny, Scott and Gibbons 2001). The culture of academia promotes and values the exploration of radically novel ideas and scientists are rewarded for perseverance in generating cross-pollinated ideas that depart from established thought (Kuhn 1993 [1962]). In contrast industry scientists are employed to engage in work that will increase the company’s profitability in the near term. The exploitation of existing knowledge yield more sure bets and less risk for the firm than novel discoveries (Nowotny, Scott and Gibbons 2003). Furthermore, it has been shown that access to industrial partners and industrial funding decreases the innovativeness of scientific research (Evans 2004). We thus hypothesize that there will be an interaction effect between proximity and cross-pollination, where industrial affiliation hinders the mobility of cross-pollinated concepts:

> *Hp3a(3b): Proximity to commerce hinders the mobility of cross-pollinated concepts between science and technology (commercialization)*

Impact of technology translation

Concept mobility from science to commercialization is often intersected by a presence in the technology space (David and Foray 1995). Many scientific concepts appear in patents before they are integrated into a product. Patents offer legal protection for the investment a firm makes in knowledge creation to prohibit that products can be reverse engineered and cheaply copied by a competitor (Mirowski and Sent 2002). Once detailed descriptions of how a scientific concept might be commercialized are outlined in a patent it is easier for the concept to subsequently be integrated into the commercial sphere. We thus hypothesize:

H4: The appearance of a concept in technology stimulates the concept's mobility into commercialization

DATA AND METHODS

Setting: Nanobiotechnology

We test our hypotheses within the field of nanobiotechnology. To choose our area of study we first conducted 11 interviews with nanoscientists at leading US research institutions, to identify the area of nanotechnology that scientists thought were most revolutionary. The interviews identified nanobio as a field of increasing importance. The nanobio field is located at the intersection of two technological areas; biotechnology and nanotechnology, which provides a rich setting for studying the effects of cross-pollination. Nanotechnology emerged out of the intersection between material science, electrical engineering and physics in the beginning of the 1980s. The invention of new methods of inventing like the atomic force microscope (Darby and Zucker 2003) enabled novel research at the nano-scale.

Biotechnology is a more established discipline that emerged at the intersection between biology and organic chemistry in the middle of the 1970s.

In the early days of nanotechnology, biotechnology was a marginal application area. During the 1990s the synergies between the biological sciences and nano-sciences emerged and the nanobio field has experienced accelerated growth ever since. A commercial nanobio field is in the making. Extraordinary scientific achievements have been accomplished and entrepreneurial firms are rapidly attempting to commercialize nanobio science (Darby and Zucker 2003). The core element that delineates the nanobio field from nanotechnology and biotechnology is that it combines biological structures with inorganic molecules. Discoveries within nanobio address diagnostics, drug development and drug delivery. Many scientists and companies are working to create "lab-on-a-chip" to aid both drug discovery and drug delivery. In one of our interviews a material scientist for example explained that he had researched nanoparticles for use in disk-drives for most of his career. Over the last couple of years he began working with researchers in molecular biology to develop better sensors and diagnostic tools. In the collaboration they combined nanoparticles, normally used in disk-drives, with genes, proteins, and enzymes to develop new cancer diagnostics. This cross-pollination of knowledge led to high rates of improvement over the existing technologies. Other scientists are taking advantages of the novel properties of nanoparticles to develop methods for drug delivery, like encapsulating a drug within a nano molecule.

We chose to study the emergence of the nano-bio field exclusively with the inventions filed in the US patent office because the United States dominates research in material and biological research. Moreover many important non-American inventions tend to be published and patented in the United States due to the importance of the American commercial and knowledge market (Hall and Trajtenberg 2004). This is particularly true for the nanotechnology field[3] (Bonaccorsi and Thoma, 2007; OECD, 2007).

Methodological motivation

Patents may be based not only on the prior art documented in other patents, but in part or fully on new scientific knowledge. Since published scientific research results can be used to illustrate the state of the art against which the application has to be evaluated, patent examiners will search for relevant references in the scientific literature. The logic of these references is to support the claims that are made in the application. Researchers have used patent citations to develop a taxonomy of industries (Grupp 1992; Heinze and Schmoch 2004; Tijssen 2004) and to document the networks of patents (Popp 2005; Verspagen 2005). The theoretical motivation for developing temporal patent networks is to grasp how knowledge develops and evolves over time.

On the methodological side, several shortcomings of the existing measures of non-patent literature should be recognized. First, it is not clear to what extent non-patent literature citations are assigned by inventors or by examiners. It is well known that inventors primarily introduce references in the USPTO, while in the European system they are introduced by the examiners. Breschi and Lissoni (2004) claimed that, at least in the US patent system, the variation in who assigns non-patent literature citations creates severe distortions in the data. The full validity of citation patterns has to be established, given that the motivations for a patent to cite other patents are rather intricate and call upon legal and strategic considerations.

Second, non-patent citations do not convey any direct information on the degree to which the scientific content was able to generate valuable innovation in future development of

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[3] By the end of 2004 there were 12.256 biotechnology patents filed within the European Patent Office versus 43.410 by the US Patent and Trademark Office. We found only 958 nanotechnology patents filed at the European Patent Office versus 4.828 at the USPTO. For a definition of a biotechnological and nanotechnological patents see the next section.

the technology. Since we know that the distribution of patents by degree of usefulness is extremely skewed, it is possible that patents with a high number of non-patent references are among those that are never used, and so have limited economic value. One approach to mitigate this limitation is given by a careful analysis of patent quality, using the indicators first proposed by Trajtenberg (1989, 1990) and later developed by Jaffe, Trajtenberg and Henderson (1993).[4] There is sufficient evidence that the economic value of patents is associated with the number and quality of citations received in other patents (Hall, Jaffe and Trajtenberg 2005; Harhoff et al. 1999; Jaffe and Trajtenberg 2002). In addition, (Agarwal and Bayus 2002; Harhoff, Scherer and Vopel 2003; Lanjouw and Schankerman 2001) have suggested a complementary metrics, i.e. the existence of patent litigation as a measure of value, because patents that assignees are willing to pay to defend have a larger economic value.

In this study we address the science and technology interaction using a novel approach. We measure how scientific concepts move between three spheres: Science, technology and commercialization. The proxy we use to measure concept mobility is the presence of keywords in three document types: Scientific articles, patents, and press releases.

Science

We used the ISI database to locate nanotechnology and biotechnology keywords during the 14-year period between 1991 and 2005. Due to the difference in age between the biotechnology and the nanotechnology fields we used two different methods to isolate biotechnology and nanotechnology keywords.

Biotechnology keywords. To single out the nanobio science field we identified scientific publications that contained both biotechnological and nanotechnological search words. We selected author specified keywords from two specialized journals in the field of

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[4] For a survey of the literature see Jaffe and Trajtenberg (2000)

Biotechnology and Applied Microbiology and Cell Biology, respectively *Biotechnology and Bioengineering* (BB) and *Embo Journal* (EMBO). Our criteria for selecting these journals were the following: First, we looked for journals there were widely read in the field: both BB and EMBO has been at top quartile of the impact factor index distribution of their field since at least 1999 (ISI JCR, 2005). Secondly, we looked for journals founded before 1991 and regularly containing authors' keywords: ISI began collecting authors' keywords regularly after January 1991. Finally, we looked for journals that targeted broad topics within the field and that published many articles in absolute terms. We isolated all keywords used in BB and EMBO in the period 1991-2005 obtaining a combined list of 28,194 biotechnology keywords.[5]

Nanotechnology keywords. Because there are no established nanotechnology journals that have been around for a long time we had to use a different search strategy to isolate nanotechnology articles. To identify nanotechnology publications we used a list of search words, defined by the ISI Fraunhofer Institute to search titles, keywords and abstracts (Fraunhofer-ISI 2002). This search strategy enabled us to retrieve a database of more than 240,000 publications from ISI for the period 1991-2004. From this set of articles, we retrieved all of their keywords, which provided us with a basic pool of nanotechnology keywords constituted by 146,484 words.

Nanobio publications. To isolate nano-bio keywords we looked at the overlap between the biotechnology and the nanotechnology keywords. This provided us with a list of 7,715 nanobio keywords.

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[5] 1153 keywords overlapped between the two journals.

Technology

As mentioned, in the following analysis we selected data from USPTO.[6] Due to endogeneity concerns we could not use the same search words to isolate nano-bio patents that we used to identify the nano-bio articles. To delineate a nano-biotechnology field we followed two search strategies according to two different knowledge constructs within the field. In the first search we isolate patents through a static process. We use the nanobio search words identified by Fraunhofer-ISI (2002)[7] listed in Table A-2. We searched for patents that had any of the search words in either the titles or abstracts during the period 1971-2004. We obtained a dataset of 1.491 patents in that period. Characteristic of these patents is that they involved a specific technique or compound that is unique to nano-bio and is found neither within nanotechnology or biotechnology.

We also employed a second search strategy to isolated patents that contained cross-pollination of knowledge from the biotechnology and the nanotechnology field. To isolate these patents we looked at the overlap between nanotechnology and biotechnology patents. Patenting propensity in the biological related fields is widely recognized in the literature and in the press (Arora and Gambardella 1994; Gambardella 1995). The US Patent and trademark office have for many years had specific patent classifications for biotechnology innovations. We use the IPC based strategy used by Schmoch (2003) to identify biotechnology patents, and search the USPTO database in the period 1971-2004.[8] This search generated a dataset of 43.310 patents. Figure 1 depicts the exponential growth in the patenting activity within the biotechnology field.

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[6] The source of data is constituted by the Delphion patent database (DPD), which is an on-line proprietary database, accessible from www.delphion.com. It includes data from different national and international Patents Offices. In particular, it offers a complete text and images of all patents issued by the US Patent and Trademark Office (USPTO) since 1971. In addition Delphion offers some complementary tools, that easy keyword based search strategies.

[7] In order to circumvent the problem of an accidental selection of keywords given by experts, they listed all terms in the patent database beginning with “nano”. An expert in the NST assessed for each term whether it is used in the context of nanotechnology and whether it indicates an unambiguous relation to this field. 40 keywords queries have been obtained, identifying singularly a field. See appendix 1 for more information.

[8] A similar definition has been adopted by the OECD (2007)

The search strategy for nanotechnology patents had to be mainly based on keywords, since the specific IPC-subclass B82B for this field was introduced in the year 2004 (Commerce 2004) and does not cover former years. We used a keyword search strategy suggested by Fraunhofer ISI Institute in Karlsruhe, which we found to be the most complete and validated by experts among the static keywords methodologies. Articles and reports have already been published using this search methodology (Bonaccorsi and Thoma 2007; Fraunhofer-ISI 2002).

We performed the search in the titles and the abstracts of the patents, and obtained a sample of 4.828 patents granted before May 2004. The nanotechnology patents, like the biotechnology patents, grow exponentially, especially in the last years (1996-2002). The USPTO has patented several thousands of inventions in nanotechnology, with around 4.500 patents filed in 2003.

To isolate the nano-bio patents corresponding to the second knowledge combination we identified the overlap between the datasets of nanotechnology and biotechnology patents. This resulted in a sample 406 patents over the period. We then combined the two datasets that we had obtained using the different search methodologies to obtain a complete sample of the nano-bio space. This yielded a total of 1.573 patents. The first patent in the field was granted in the 1975, but only during the 1990s did the growth in nano-bio patenting begin to accelerate.

Commercialization

The commercialization of a scientific and technological concept involves creating new products. We tracked the commercialization of concepts by retrieving company press releases - newswires - in the Lexis-Nexis database over the period 1980-2005.[9] Our search strategy was

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[9] The Lexis-Nexis newswire database delivers full-text, unedited news releases as written by the originators. The releases cover a broad range of topics including quarterly and annual earnings, dividends, earnings forecasts, new stock issues, debt financing, mergers and acquisitions, antitrust actions, tender offers, new products and

two fold. The first was based on the same nano-bio keywords that we used for patents, obtaining a sample of around 2,307 news events. Second, we considered the events that the announcing firms classified as pertaining to the biotechnology and nanotechnology industries. The second search strategy yielded an output of 730 press releases. We combined the two search strategies, obtaining 2837 press releases.

OPERATIONALIZATION AND MEASURES

The unit of analysis used in this paper is *concepts* measured as keywords in a given year. We analyze how scientific concepts move between three institutional areas: Science, technology and commercialization represented by scientific articles, patents, and press releases.

We considered in the analysis only the *authors' keywords*, which are self-revealed by authors in scientific publications. These keywords are stated by authors and not computer generated through an algorithm. Using only authors' keywords increase the validity of our measures.

ISI began to systematically collect authors' keywords in 1991, which is the year that we start our analysis. In the sample we excluded the keywords that are composed by three letters or less, thus reducing the probability of having homonym matched keywords[10]. We isolated 133,128 nanotechnological and biotechnological keywords over the period 1991-2004, as we defined before. We tracked the occurrence of these keywords in scientific publications over the period 1991-2004, having a non balanced panel of 243,022 observations.[11]

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production statistics, executive appointments and resignations and reactions to government regulations or court decisions.

[10] An example of a homonym is matching "ATM" with "ATM", even though it in the first instance is used as an abbreviation for "Atomic Force Microscope" and in the second instance as an abbreviation for "Automatic Teller Machine".

[11] We used also some dataming algorithms to standardize the keywords in order to avoid problems of homonymy. A full list of the algorithms is available from the authors under request.

Dependent variables. To test out hypothesis we develop the following two variables:

TECH: Measures the extent to which a scientific concept is integrated as part of a technology. TECH is a count variable measuring the occurrences of a specific keyword in a nanobio patent (title, abstract, or claims) the year after the keyword occurred in a scientific publication.

COM: Measures the extent to which a concept has been commercialized. COM counts the occurrences of a keyword in the title or body of a nanobio newswire in the year after the keyword occurred in a scientific publication.

Independent variables: They are operationalized in two dimensions:

CROSS: Measures the cross-pollination effect. CROSS is a binary variable, which takes on a positive value if in a given year a keyword has occurred in an article with both nanotechnological and biotechnological keywords.

PROX: Measures the "proximity argument". It is a count variable, which measures the number of keyword occurrences in an article, where at least one author is affiliated with a commercial firm.

Control variables. They include the following factors:

LENGTH: Measures the length of a keyword. LENGTH is a count time invariant variable, calculated by the number of letters in the keyword.

ABS_USE: Measures the diffusion of a keyword in science. It is a count variable, calculated by the number of occurrences of a keyword in sciences in a given year.

INTER: Measures the interdisciplinary effect and controls for journal effects. It is a count variable, constituted by the mean number of fields in which a keyword appears according to the ISI journal citation report on subject categories.

The descriptive statistics of the variable are reported in Table 1. We implemented a cleaning procedure for non ASCII standard and alphanumeric characters, removing and condensing the blank spaces, tabulations, commas and other word separators. Then we collapsed the occurrences of the cleaned keywords. As we can notice from Table 1, the average values of keyword occurrences are very low: the average diffusion in Science – ABS_USE - is 2.11 and the median 1, and a similar scaling factor for TECH and COM. The standard deviation are very large compared to the mean value, suggesting highly skewed distributions with a bunch of keywords frequently occurring in publications, patents and newswires and large majority of keywords that are rarely used. This is also confirmed by the maximum value statistics. Examples of frequent keywords are: Nanoparticle, Biosensor, Nanoarray, Celladhersion, and Biodegradablepolymer.

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Table 1 about here

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Table 2 depicts the correlation between the variables. The highest correlated variables are TECH and COM with a correlation coefficient of 0.33. This high correlation is not surprising given that if a concept has already been incorporated into a patent then the concept is also likely to later be commercialized. The correlation between INTER and CROSS is only 0.026 pointing to the fact that cross-pollination and interdisciplinary are two different measures of knowledge characteristics. Indeed, CROSS is measured at the level of the individual article whereas INTER is derived from ISI categorizations of the journal.

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Table 2 about here

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EMPERICAL RESULTS

Growth of the field

Scientific developments. Since the early 1990s nanotechnology has undergone a dramatic development. Figure 1 shows the growth in nanotechnology and nanobio with 1991 as the base year. To create the graph we divided the stock of publications in a given year by the stock of publications in 1991 to compare the growth in the general nanotechnology field to the growth of nanobio. Nanotechnology has undergone an exponential growth in the number of nanotechnology publications, but the growth rate for the nanobio field has been higher than the growth rate for the nanotechnology field. Figure 2 shows that during the period 1991 to 2003 the nanobio field grew from constituting 25 per cent to about 28 per cent of the overall nanoscience field. The growth rate of nanobio was thus significantly higher than the overall growth in nanotechnology.

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Figure 1 and 2 about here

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Technology developments. The rapid growth of nanobio science is paralleled within nanobio technology. Figure 3 depicts the dynamics of biotechnology, nanotechnology and nanobio over time. Both nanotechnology and biotechnology have experienced an exponential growth in the production of patents during the 1990s and early 2000s. The growth rate within the nanobio field was, however, much higher than in its two parent fields. Whereas the stock of biotechnology patents has risen nearly 9 times from 1990 to 2004, and the stock of nanotechnology patents had risen nearly 15 times from 1990 to 2004 then the stock of nanobio patents has risen an extraordinary 54 times from 1990 to 2004.

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Figure 3 about here

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Commercialization development. Figure 4 illustrates the growth in press releases containing nanobio concepts from the first press release from 1991 to 2005. During the 1980s there was a slow growth within nanobio commercialization and it was not until 1990 that the commercialization of nanobio really escalated. Another dramatic increase in the amount of nanobio press releases happened around year 2000 with the following years producing hundreds of nanobio announcements.

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Figure 4 about here

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Determinants of Growth

We used a negative binomial count regression model for the estimation of the stated hypothesis, since our dependent variables take on nonnegative integer and not upper bounded values. The Poisson regression model relies on less restrictive assumptions because it allows for potentially variance dispersion of the dependent variable with respect to its mean value. Although we do not have a prior to the distribution of our depended variables, a less restrictive regression model is strongly suggested for a preliminary investigation (Wooldridge 2002). Moreover we adopted two estimation approaches. First we estimated a pooled negative binomial estimator, including in all the regressions year dummies. While this technique allows us to use a large number of observations in the estimation, it does not rule out potential endogeneity of the independent variables, that is the correlation of explanatory variables with the disturbance. If this assumption is violated then the consistency of estimates cannot be obtained with a pooled regression approach.

Second, to overcome the potential endogeneity of the explanatory variables and check the robustness of the results we estimated a fixed effect negative binomial estimator. The fixed effect estimator reduced the dataset to the keywords that appear in more than one period: by placing a dummy for each specific keyword in the dataset, it estimates the impact on the dependent variable of unobserved and time constant effect that might source of potential correlation across the explanatory variables and the disturbance. As showed firstly by Hausman, Hall, and Griliches (1984) this estimator has desirable robustness and consistent properties.

The results of the pooled negative binomial estimator are found in table 3 and table 4, whereas table 5 depicts the results of the fixed effect panel estimation of the negative binomial count model to control for unobserved heterogeneity at the level of the keyword. The fixed effect panel estimation is restricted to keywords that occurred in at least five different years.

Hypothesis 1a and 1b: We find support for hypothesis 1a and 1b. If a concept appears together with keywords pertaining to both nanotechnology and biotechnology then the concept has a higher likelihood to both subsequently be integrated into a technology and to be commercialized. This result supports our hypothesis that cross-pollination between concepts from different disciplines creates ideas that are more likely to proliferate. Interestingly, this positive effect of cross-pollination occurs in addition to the rough measure of whether a concept was published in a journal that spans multiple disciplines. Publication of the concept in an interdisciplinary journal actually positively impacts the possibility that the concept will later be commercialized, but the effect is smaller. In terms of elasticities, the panel estimation suggests a standard deviation increase in the cross-pollination effect has a positive impact of about 13.2% in the probability of being incorporated in the technology and 4.7% to later be commercialized.

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Table 3, 4, and 5 about here

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Hypothesis 2a and 2b: We find support for hypothesis 2a and 2b at the 1% significance level. If a person affiliated with a private company presents a concept in a scientific article then the concept has a higher likelihood of subsequently being incorporated into a technology and of being commercialized.

The effect of proximity to market is much smaller than the effect of cross-pollination both in the pooled and fixed effect panel regressions. In the latter case, if a keyword occurs in an article that contains nanotechnology and biotechnology concepts, then the likelihood that it will be incorporated in a patent is 13.2% higher than if no cross-pollination occurs. If an author is affiliated with a private company the likelihood that the concept will be translated into a technology is only 4.5% higher than if all the authors are scientists. Similarly, if a concept is published in an article that contains both nanotechnology and biotechnology concepts then the likelihood that it will later be commercialized is about 4.7% higher than if no cross-pollination occurs, whereas the effect of the industrial affiliation of one of the authors is only 1.7%.

Hypothesis 3a and 3b: We find support for both hypothesis 3a and 3b at the 1 % significance level. The interaction effects have negative coefficients, which indicate that the positive effect of cross-pollination between nanotechnology and biotechnology for the probability that the concept will be commercialized only holds true if the authors are scientists. If the authors instead are affiliated with a company, cross-pollination actually has a negative effect on both the probability that it will be incorporated into a technology and that it will later be commercialized.

Hypothesis 4: We find support for hypothesis 4 at the 1% significance level. If a concept has already been incorporated into a technology it is 9% more likely that it will subsequently be commercialized. In the pooled regressions this effect is the second most powerful predictor of whether a scientific concept will be commercialized, although it is small in panel estimation.

Overall goodness of the model: Overall the model has statistically significant explanatory power, especially considering the limited number of variables included in the model. The model explains 17% of the variance with regards to whether a concept will be incorporated into a technology, and 11% of the variance with regards to whether a concept will subsequently be commercialized. These results show the strong predictive value of the mobility of concepts between science, technology and commercialization.

DISCUSSION

The growth of new industries and commercial fields is central to the sustainability of economic growth within a modern society (Arora, Landau and Rosenberg 1998; Rosenberg 1998). Chemical engineering, for example, emerged from the oil and petroleum refining and dyes industries during the late 19th century. Indeed, the benefits to overall economic growth from discoveries made in chemical engineering were substantial and unfolded for decades.

In this paper we show that a new field is emerging at the intersection between nanotechnology and biotechnology. This field is growing more rapidly than its two parent fields nanotechnology and biotechnology. Our results show that the success of the field is partly driven by a cross-pollination of knowledge between nanotechnology and biotechnology. We base our analysis on robust estimation techniques – such as fixed panel estimation which allows to control for unobserved heterogeneity at the level of the single keyword – and document that concepts that appear in scientific articles, which contain both nanotechnology and biotechnology concepts, have a higher likelihood of later being incorporated into technology and subsequently be commercialized. Studies have documented that the cross-pollination of knowledge generates more creative ideas and concepts (Hargadon and Sutton 1997; Hargadon 2003). We, however, show that the cross-pollination of knowledge also contributes to knowledge dynamics by facilitating concept mobility.

We further show that the mobility of scientific concepts into technology is aided when one or more of the authors are affiliated with industry. It has been debated which role scientists with industrial affiliation play in the translation of knowledge between science and technology. Some researchers have claimed that industrial scientists only publish their findings in scientific journals if the knowledge does not have commercial value (Bird, Hayward and Allen 1993). The argument behind this claim is that companies are reluctant to share any information that might provide their competitors with increased insight. Companies might thus choose to only publish information that is basic research, and thus far away from commercial possibilities. Our results counter this hypothesis. The concepts presented by industrial affiliates have a larger chance of appearing in a patent. Companies thus present concepts within scientific articles that contain commercial value.

Studies have found research conducted by or in collaboration with industrial partners is less innovative than research done purely for the sake of science. Evans (2004) shows that industrial partners and industrial funding decreases the innovativeness of plant biotechnology research. Within the nanobio field industrial affiliates also display conservatism in their publishing efforts. First industrial affiliates have a higher tendency than university scientists to include concepts in their publications that are common. Second the strong positive effect on commercialization of cross-pollinating concepts from nanotechnology and biotechnology is reversed for industrial affiliates. If a concept is published together with a person that works in a company cross-pollination diminishes the probability that the concept will be commercialized. This result shows conservatism among industrial affiliates, because they are not engaged in commercializing innovative cross-pollinated concepts.

Future research might address the effect that the integration of a concept into a technology and the commercialization of a concept have on scientific development. In particular, the direction might be that of disentangling the existence and the intensity of the feedback reinforcing processes of technological and industrial developments onto scientific production.

Many scholars have criticized the linear model of innovation, which only describes a movement of concepts from science to technology and subsequently to commercialization, but not the reverse knowledge flow (Kline and Rosenberg 1986; Mowery and Sampat 2005). Rosenberg (1982) has provided in-depth historical accounts of how industrial development aids the growth of science, by both providing scientists with results unexplainable by existing scientific theories, and by developing tools that facilitates data collection. This important dynamic relationship between science and technology has, however, not been tested on a large empirical dataset. Future research might thus explore the role of cross-pollination in stimulating the mobility of concepts from commercialization to science.

FIGURES AND TABLES

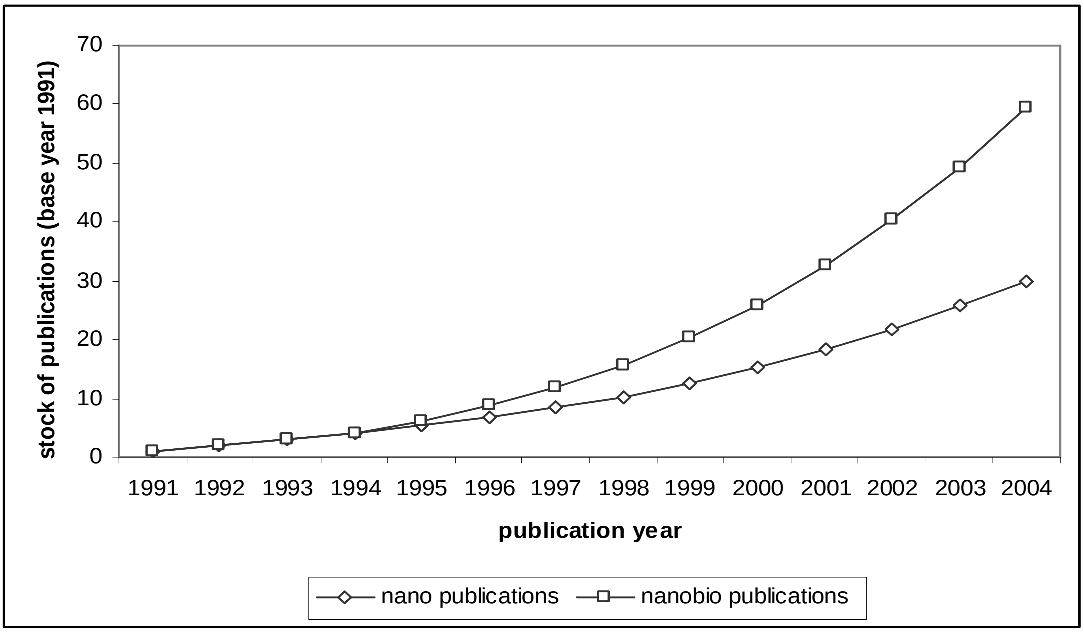


FIGURE 1: Cumulative Entry of Nano and Nanobio Publications (base year 1991)

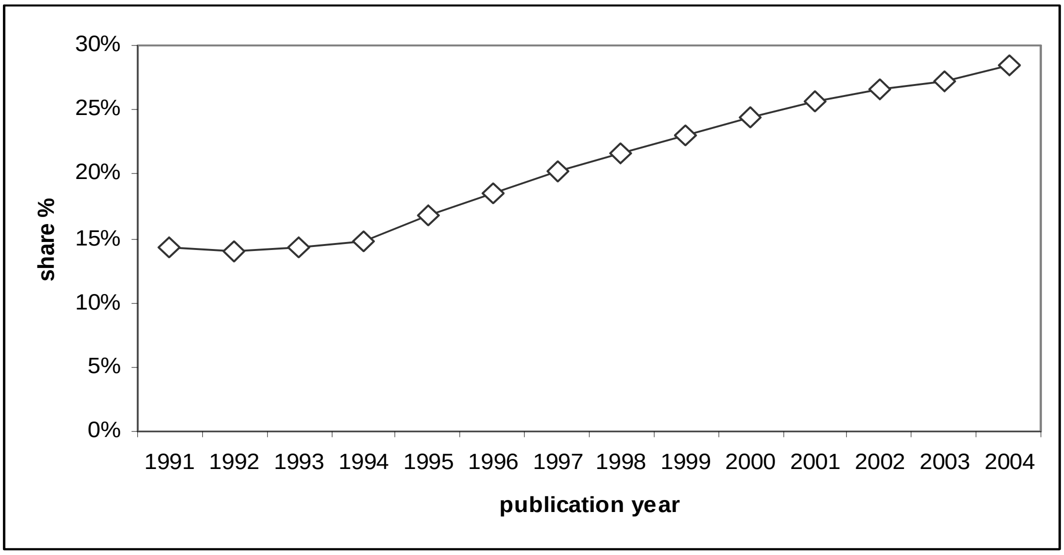


FIGURE 2: Importance of Nanobio field within Nano Science

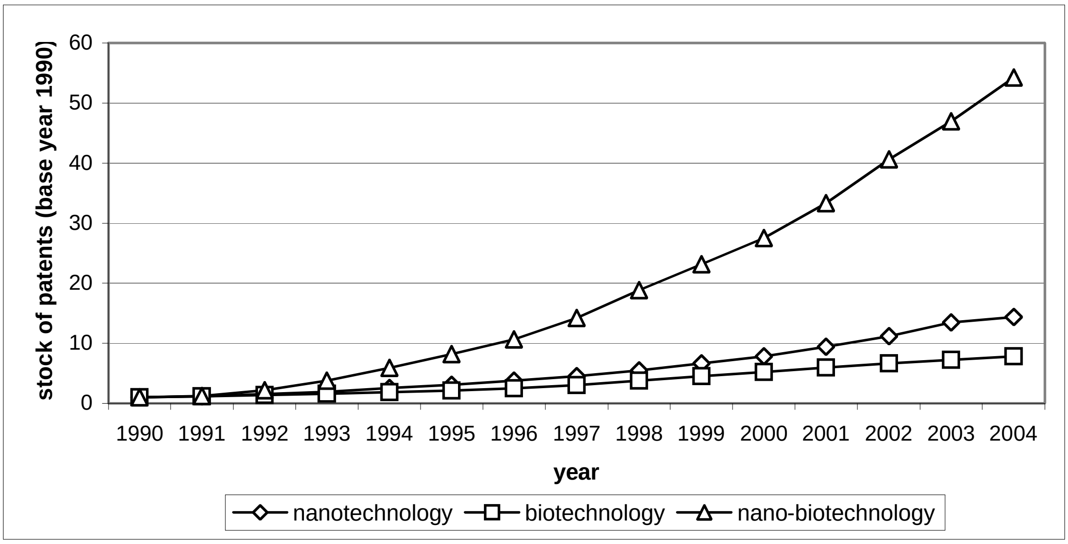


FIGURE 3: Nano – Biotechnology patents over time base year 1990

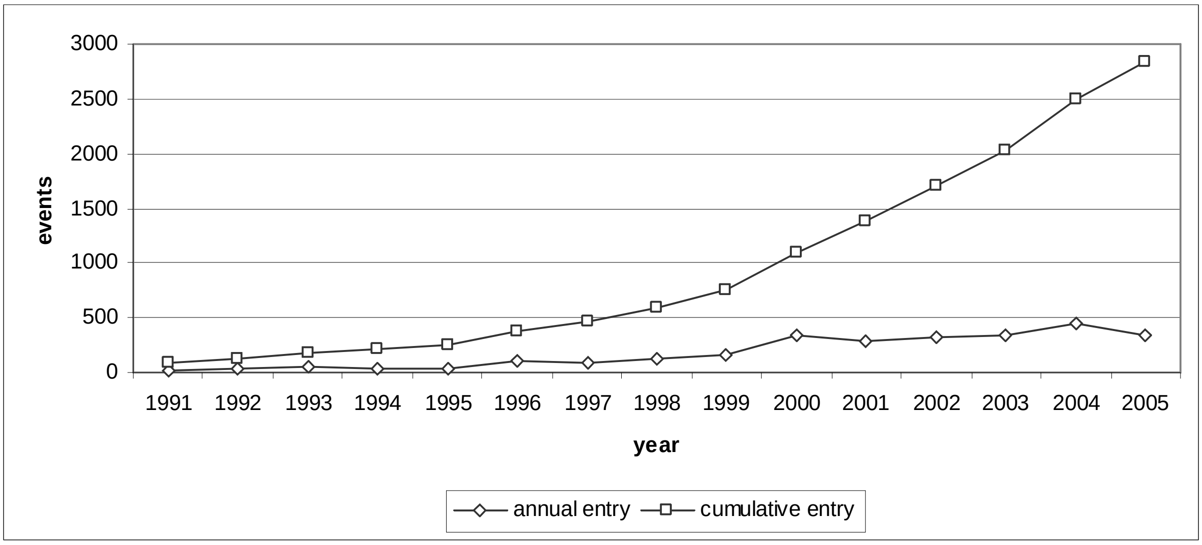


FIGURE 4: Nano – Biotechnology news-events over time

Notes: The events of 2005 regard only those announced in the first 9 months of the year.

TABLE 1 Descriptive Statistics

(243,022 observations, 133,128 distinct keywords)

	Min	Max	Mean	Std	Median
TECH	0	202	0.13	1.72	0
COM	0	680	0.68	66.45	0
CROSS	0	1	0.03	0.03	0
INTER	1	15	1.68	0.69	2
PROX	0	57	0.24	0.85	0
LENGTH	5	133	16.70	60.86	16
ABS_USE	1	499	2.11	47.38	1

TABLE 2 Correlation matrix among the explanatory and control variables

(243,022 observations, 133,128 distinct keywords)

	TECH	COM	CROSS	INTER	PROX	LENGTH	ABS_USE
TECH	1.000						
COM	0.327	1.000					
CROSS	0.072	0.041	1.000				
INTER	0.004°	0.007	0.026	1.000			
PROX	0.056	0.043	0.072	0.072	1.000		
LENGTH	-0.098	-0.094	-0.097	-0.001°	-0.039	1.000	
ABS_USE	0.067	0.054	0.151	0.082	0.733	-0.051	1.000

Notes: All the correlations are significant at 1% level with the exception of those labeled by °

TABLE 3: Negative binomial estimation of the determinants of the keyword occurrence in patents

(243,022 observations, 133,128 distinct keywords)

	MODEL 1			MODEL 2			MODEL 3		
	Coeff.	std	sign	Coeff.	std	sign	Coeff.	std	sign
CROSS	1.33	0.05	***	0.87	0.05	***	0.97	0.05	***
PROX	0.33	0.02	***	0.06	0.02	***	0.08	0.02	***
COM LAG	0.21	0.01	***	0.11	0.00	***	0.11	0.00	***
CROSS*PROX							-0.18	0.04	***
INTER	0.08	0.02	***	0.11	0.02	*	0.11	0.02	**
LENGTH				-0.18	0.00	***	-0.18	0.00	***
ABS-USE				0.00	0.00	***	0.06	0.00	***
YEAR DUMMIES	yes			yes			yes		
COSTANT	yes			yes			yes		
Pseudo R2		11%			16%			17%	
Elasticities at the mean value									
CROSS	5.7%	0.00	***	1.9%	0.00	***	2.2%	0.00	***
PROX	1.4%	0.00	***	1.0%	0.00	***	1.0%	0.00	***
COM LAG	0.9%	0.00	***	0.2%	0.00	***	0.2%	0.00	***
CROSS*PROX							-0.4%	0.00	***

Notes: *** 1% level significance; ** 5% level significance; * 10% level significance

TABLE 4: Negative binomial estimation of the determinants of the keyword occurrence in newswires

(243,022 observations, 133,128 distinct keywords)

	MODEL 4			MODEL 5			MODEL 6		
	Coeff.	std	sign	Coeff.	std	sign	Coeff.	std	sign
CROSS	1.36	0.07	***	1.00	0.06	***	1.11	0.07	***
PROX	0.28	0.02	***	0.20	0.02	***	0.22	0.02	***
TECH LAG	0.21	0.01	***	0.88	0.02	***	0.88	0.02	***
CROSS*PROX							-0.22	0.05	***
INTER	0.02	0.02	***	0.05	0.02	***	0.06	0.02	**
LENGTH				-0.23	0.00	***	-0.18	0.00	***
ABS-USE				0.04	0.00	***	0.04	0.00	***
YEAR DUMMIES	yes			yes			yes		
COSTANT	yes			yes					
Pseudo R2	5%			10%			11%		
Elasticities at the mean value									
CROSS	39.3%	0.02	***	10.1%	0.01	***	11.2%	0.01	***
PROX	8.0%	0.01	***	2.0%	0.00	***	2.2%	0.00	***
TECH LAG	42.3%	0.01	***	8.9%	0.00	***	8.9%	0.00	***
CROSS*PROX							-2.2%	0.00	***

Notes: *** 1% level significance; ** 5% level significance; * 10% level significance

TABLE 5: Negative binomial fixed effect panel estimation

(78,830 observations, 10,109 keywords occuring in at least 5 year periods)

	MODEL 7 Patents			MODEL 8 Newswires		
	Coeff.	std	sign	Coeff.	std	sign
CROSS	0.13	0.03	***	0.05	0.02	**
PROX	0.04	0.01	***	0.02	0.01	***
COM LAG	0.00	0.00	***			
TECH LAG				0.01	0.00	***
CROSS*PROX	-0.03	0.01	***	-0.02	0.00	***
INTER	0.04	0.01	***	0.02	0.01	**
LENGTH	-0.12	0.00	***	-0.16	0.00	***
ABS-USE	0.00	0.00		0.01	0.00	***
YEAR DUMMIES	yes			yes		
COSTANT	yes			yes		

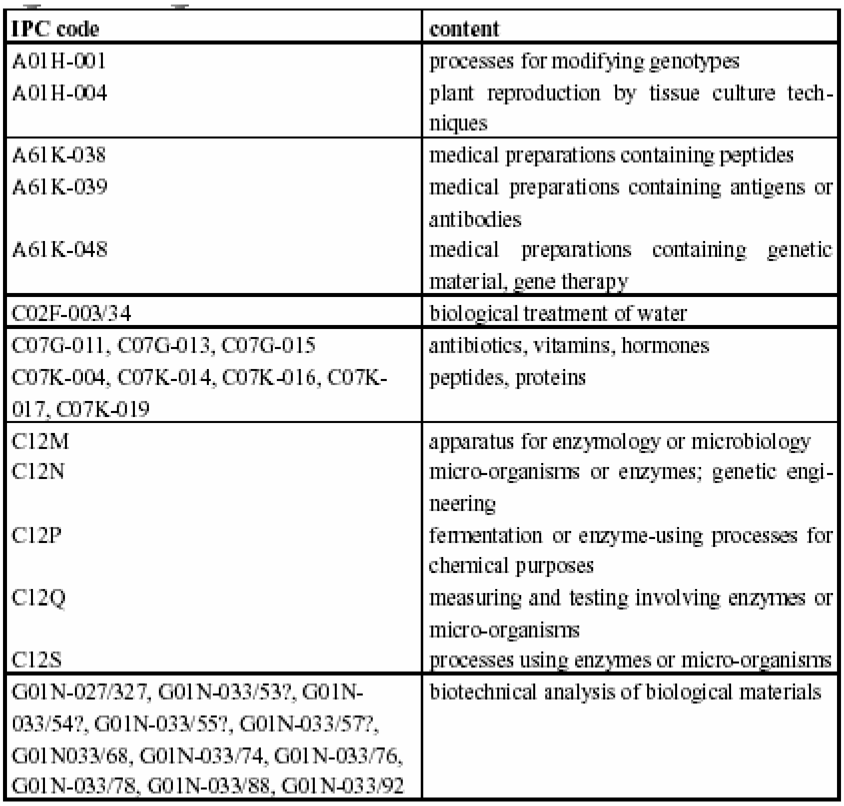
Elasticities at the mean value

CROSS	13.2%	0.03	***	4.7%	0.02	**
PROX	4.5%	0.01	***	1.7%	0.01	***
COM LAG	0.2%	0.00	***			
TECH LAG				1.9%	0.00	***
CROSS*PROX	-3.0%	0.01	***	-1.6%	0.00	***

Notes: *** 1% level significance; ** 5% level significance; * 10% level significance

APPENDIX

Table A-1 Definition of Biotechnology Patents



IPC code	content
A01H-001	processes for modifying genotypes
A01H-004	plant reproduction by tissue culture techniques
A61K-038	medical preparations containing peptides
A61K-039	medical preparations containing antigens or antibodies
A61K-048	medical preparations containing genetic material, gene therapy
C02F-003/34	biological treatment of water
C07G-011, C07G-013, C07G-015	antibiotics, vitamins, hormones
C07K-004, C07K-014, C07K-016, C07K-017, C07K-019	peptides, proteins
C12M	apparatus for enzymology or microbiology
C12N	micro-organisms or enzymes; genetic engineering
C12P	fermentation or enzyme-using processes for chemical purposes
C12Q	measuring and testing involving enzymes or micro-organisms
C12S	processes using enzymes or micro-organisms
G01N-027/327, G01N-033/53?, G01N-033/54?, G01N-033/55?, G01N-033/57?, G01N033/68, G01N-033/74, G01N-033/76, G01N-033/78, G01N-033/88, G01N-033/92	biotechnical analysis of biological materials

Source: (Schmoch 2003) Fraunhofer ISI, Karlsruhe, Germany; reported also in OECD (2007)

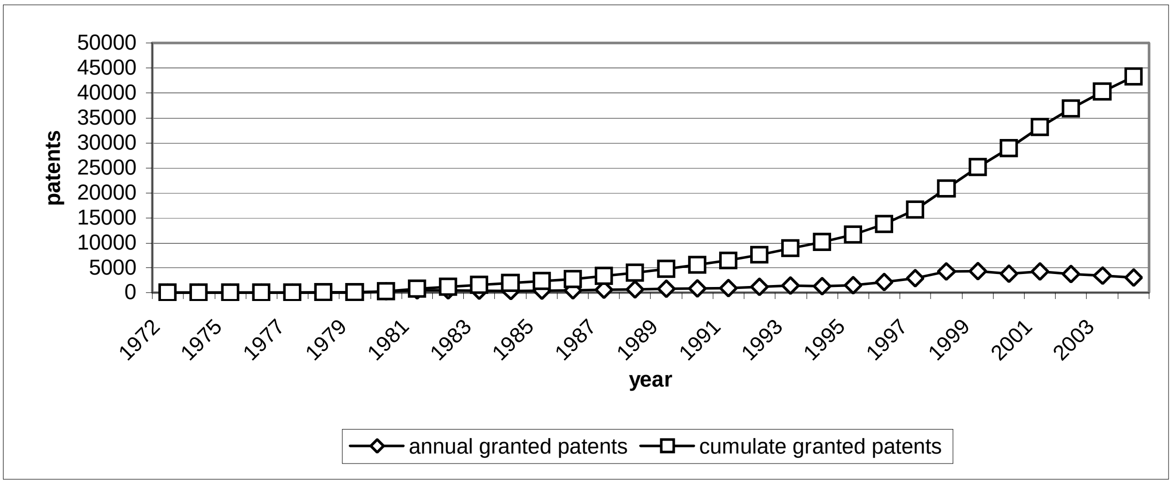


Figure A-1 Entry of patents in biotechnology by publication year

Source: USPTO

Table A-2 Keywords based search strategy for nano bio patents

```
S (BIOCHIP OR BIOSENSOR) AND (A61# OR G01N OR C12Q)/IC
S DNA(W)CMOS
S (BACTERIORHODOPSIN OR BIOPOLYMER# OR BIOMOLECULE#)AND (G11# OR G02# OR G03# OR G06#)/IC
S BIOMOLECULAR TEMPLAT? OR VIRUS(2A)ENCAPSULATION OR MODIFIED VIRUS
S NANO? AND IMPLANT?
S (PATTERN? OR ORGANIZED) AND (BIOCOMPATABILITY OR BLOODCOMPATABILITY OR BLOOD COMPATABILITY OR CELL SEEDING OR CELLSEEDING OR CELL THERAPY OR TISSUE REPAIR OR EXTRACELLULAR MATRIX OR TISSUE ENGINEERING OR BIOSENSOR# OR IMMUNOSENSOR# OR BIOCHIP OR CELL ADHESION)
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