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The global institutionalization of nanotechnology research: A bibliometric approach to the assessment of science policy

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Based on bibliometric methods, this paper describes the global institutionalization of nanotechnology research from the mid-1980s to 2006. Owing to an extremely strong dynamics, the institutionalization of nanotechnology is likely to surpass those of major disciplines in only a few years. A breakdown of the relative institutionalizations strengths by the main geographical regions, countries, research sectors, disciplines, and institutional types provides a very diverse picture over the time period because of different national science policies. The results allow a critical assessment of the different science policies based on the relative institutionalizations strengths as well as the conclusion that the institutionalization process has run out of control of individual governments who once induced the development.

Introduction

One might think that a study of the institutionalization of nanotechnology research is already obsolete. Indeed many governments and investment firms have produced a

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wealth of reports on the growth of nanotechnology.[1] Particularly the US National Nanotechnology Initiative (NNI) and its precursor organization, the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), have in several reports carefully analyzed the nanotechnology activities in Asia and Europe in order to prepare their own activities, which again have been well documented. In addition, several international conferences have been organized and documented, in which national representatives have exchanged information about their past and future nanotechnology activities. Moreover, numerous investment firms, business consultants and nanobusiness alliances have collected facts about industrial and governmental nanotechnology activities worldwide that illustrate the steep rose of a new market.

However, there are two main reasons why all these reports do not adequately describe the institutionalization of nanotechnology research. First, both governmental agencies and investment firms are not neutral observers but actors in that process. Once they have decided to make nanotechnology a priority funding area, governmental agencies tend to exaggerate greatly their national activities, particularly if they see themselves in an international competition. Since the reports by investment firms have no other purpose than to attract investors, there is any reason to mistrust them. As long as nanotechnology remains vaguely defined, the compilations of nanotechnology activities can easily be adjusted to any need. Secondly, the reports by both actors do not describe the institutionalization of nanotechnology research but are largely confined to the amounts of money that go into research infrastructures and that are expected to come out on the market. However, the institutionalization of research is a social phenomenon for which money might act as an incentive, but by no means as an indicator. After all, science policy has many different instruments and the political art is to select those instruments that lead to the best results with the same amount of money. It would be foolish to describe the results (institutionalization) in terms of the instruments (governmental activities). Thus, if the institutionalization of nanotechnology is the desired political goal, only a study of this institutionalization process can in retrospect assess the efficiency of the political instruments that have actually been used. For that purpose, we need to describe the institutionalization in terms that are strictly independent of the reports.

Apart from the assessment of science policies, a study of the institutionalization of nanotechnology is important also from a science studies perspective. Nanotechnology has arguably been the strongest movement in the re-organization of the disciplinary

[1] There are literally hundreds of such reports now, mostly available online only, that cannot be listed here; for instance from the US by the NNI (www.nano.gov/html/res/pubs.html); for Europe, by the European Union (http://cordis.europa.eu/nanotechnology) and Nanoforum (www.nanoforum.org); for the Asian-pacific region, by Japan's AIST (www.nanoworld.jp/apnw/articles/japan.php) and the Asian-Pacific Nanotechnology Forum (www.apnf.org). Pure business reports have been produced, for instance, by Forbes/Wolfe (www.forbesinc.com/newsletters/nanotech/), Lux Research (www.luxresearchinc.com), US Nanobusiness Alliance (www.nanobusiness.org), nABACUS (www.nabacus.com), Cientifica (www.cientifica.com), Piribo (www.piribo.com) as well as by dozens of individuals. (All websites accessed 15 August 2006.)

landscape of science and engineering worldwide in the past decade. Where did that movement come from – from which disciplines and geographical regions? What have been the driving forces – universities, governments, or industries? What kinds of international, inter-disciplinary, and inter-institutional dynamics rule the movement? In what direction does the institutionalization of nanotechnology move – towards the formation of a new discipline, several new sub-disciplines, the blurring of disciplinary boundaries and identities for increased interdisciplinarity, or towards a new flexibility in the use of fashionable brands?

Of course, the present study cannot answer all these question.[2] Rather it is an attempt to approach both science policy issues and science studies issues by bibliometric methods.

Methodology

This study uses a simple bibliometric method that nonetheless provides both quantitative indicators and qualitative material to describe in detail the institutionalization of nanotechnology research. The method is based on two assumptions that each requires brief discussion:

(1) The institutionalization process is reflected, though not fully comprehended, by the establishment of research institutions that use the prefix "nano" in their official names, which will be called "nano-institutions" in the following. As with any other study on nanotechnology, studying the institutionalization is faced with the problem that nanotechnology research is only vaguely defined and covers diverse, internationally differing, and increasingly more research fields. While the loose identity creates strong difficulties in most studies of nanotechnology, it is less so in the study of the social processes. Regardless of what nanotechnology is in terms of research topics, the institutionalization of research is a social process of creating a social identity, for which the use of a common name is a good indicator. However, there are two important exceptions that require extra consideration. First, in Japan the term "atom technology" was temporarily used, indeed prescribed by government, in names of institutions that before and afterwards used the term "nano". Second, more recently research institutions emerged with additional prefixes in their names, of which "bionano" is the most common one, but still rare enough to be neglected.

(2) The institutionalization process can be quantitatively measured by the number of research papers from such nano-institutions over the time. One might object that it is not the number of papers but the number of institutions that should count. However, since this study deals with the institutionalization of nanotechnology *research*, it is necessary to quantify the nano-institutions in terms of their research activity and ignore

[2] For some earlier answers, see SCHUMMER (2004).

those that are only paper constructs. Thus a research-active nano-institution contributes more to the institutionalization than a less active one. It is also more visible by the research community and thus has more reputation and impact on others. On the other hand, the focus on papers excludes other research publications, like books and patents. The neglect of patents is indeed a deficit because it underestimates the institutionalization of industrial nanotechnology research, for which we can therefore draw only relative conclusions.

Based on these two assumptions, samples from the SCI-Expanded database were drawn with the search term "nano*" in the address field: for the first eleven years (1984-1994) the complete sets and for the following years (1995-2006) each a random sample of 150 papers.[3] The affiliation addresses of the thus identified nano-institutions were then analyzed according to five categories: (1) the research sector (university, governmental, or industrial research institutions); (2) the type the of nano-institution (group, lab, center, department, etc.); (3) the level of the nano-institution within the author's main institution; (4) the discipline with which the nano-institution is associated, if recognizable in the address; (5) the geographical region and the country of the nano-institution. In addition, the complete address data set was used for a qualitative historical analysis of the establishment of nano-institutions worldwide.

The use of the SCI database has several shortcomings. First, it has a clear bias in favor of US publications, since it includes, for instance, even unpublished papers of the meetings of the American Chemical Society as "articles" and strongly neglects non-English publications. Therefore the degree of the institutionalization of nanotechnology in the US is likely to be overestimated, but the relative trends should be accurate. Second, ISI does not attribute affiliations to individual authors so that, if one author provides two different affiliations, say, one to a nano-center and one to a chemistry department at the same university, important information is lost. Moreover, customs differ between researchers and journals if the two affiliations are combined into one byline or not, but these differences are expected to be leveled out for each year.

Of course, each of the categories requires clear-cut distinctions that cannot easily account for borderline cases. For instance, the distinction between universities, governmental, and industrial research institutions is undermined by governmental or industrial research units located at or associated with universities. As a rule, decisions have been made strictly according to the address details, such that, for instance, a national research center located at a university has been counted as university only if the university appears in the address. Indeed many such centers historically moved from university labs to governmental research institutes resulting in changing address details. There are also some governmental research institutions, particularly in Asia, that offer

[3] Samples have been drawn with statistical care covering the entire year because the data sets are not equally distributed in the database according to geographical regions. For 2006, only the first half-year has been considered in August 2006, which might result in some deviations.

advanced degree programs, which were then counted as universities, so that governmental research institutions might be slightly underestimated there.

The type of the nano-institution (group, lab, center, department, etc.) is always clearly indicated in the affiliation address, but the meaning of these terms at universities differs between countries to some degree. For instance, a lab can be a sub-unit of a department, similar to a group, or an interdepartmental facility. A center can be anything between a rather informal, in fact decentralized, association of researchers and a strong unit with an own building and administration that operates independently from departments. Institutes can be both sub-units and equivalents of departments. On average, however, groups, labs, institutes, and departments at universities are units of increasing size and degree of stabilization. Initiatives, projects, programs, networks, consortia, and centers are, at least at the beginning, more temporary institutions in the sense that they are less embedded in the existing university structure, but usually broader in their multi-disciplinary orientation. The two sets of institutions thus indicate different possible pathways and models for the institutionalization of nanotechnology research. The first pathway corresponds to a *disciplinary model of institutionalization* that aims to establish nanotechnology as a discipline within the departmental structure of universities. The second pathway corresponds to a *cross-disciplinary model of institutionalization* that aims to establish nanotechnology as a cross-disciplinary institution.

Altogether the data allows characterizing the institutionalization process with several parameters. The number of papers by all nano-institutions at a certain time describes the *institutionalization strength*, and the growth rate the *institutionalization dynamics*. The share of papers by different geographical regions, countries, research sectors, or disciplines indicates their relative *institutionalization strength*. And the *type and level of institutionalization* is provided by the type and level of the institutions. If we find different models of institutionalization in different regions or countries, we might be able to assess the relative success of these models from their relative institutionalization strengths and dynamics. And if these models have been induced by different science policies equally aiming at a strong institutionalization of nanotechnology, that also allows assessing the success of these policies.

Institutionalization dynamics and relative geographical strengths

Before discussing the institutionalization dynamics of nanotechnology it is important to recall that science overall has exponentially grown for centuries with annual growth rates of 4-5% regarding any meaningful indicators such as the number of papers, scientists, journals, and institutions. The growth of nanotechnology must be considered in that context and is best represented on a logarithmic scale where stable growth rates translate into the slopes of straight lines. Figure 1 compares the institutionalization dynamics of nanotechnology with those of two established disciplines, physics and materials science & engineering, measured by corresponding methods.[4] In terms of their institutionalization strengths, the mature discipline of physics grows on average, similar to science overall, at 4.4% per year, whereas the relative young discipline of materials science & engineering has still an extremely high annual growth rate of 10.8%. Against that background, the average annual growth rate of 54% of nanotechnology institutions since the late 1990s appears astronomic. Of course, in the early state of the emergence of a field, new institutions are established at a much higher speed, but at much lower absolute numbers; an example is the establishment of bionano-institutions since about 2002 (Figure 1). However, nanotechnology institutions have grown at a tremendous speed since almost 20 years to a very high level nowadays. In terms of the institutionalization strength in 2006, nanotechnology has reached a level that corresponds to 10% of physics and 35% of materials science. If one extrapolates these trends, the institutionalization strength of nanotechnology will surpass that of materials science in about two years and that of physics in five to six years. Therefore, it is likely that in a few years there will be more research institutions of nanotechnology than those of materials science, physics, or any other classical discipline![5]

An annual growth rate of 54% means that numbers double every 19 months. Of course that cannot be achieved by enlarging existing institutions but only by establishing new ones. Therefore, on average more than half of the institutions in every year are new ones. If nano-institutions show a clear profile according to our categories in one year, that profile can drastically change the next year owing to the establishment of a different kind of nano-institutions. Thus, although the overall growth rate in Figure 1 appears rather smooth, extreme (non-statistical) fluctuations are expected once we break down the development according to the categories. That is particularly the case in the early time period, when still a manageable number of nano-institutions existed and a single new one could make a strong impact. For most of the time period, however, fluctuations have been owing to the fact that new countries discovered nanotechnology and quickly established their preferred type of institutions.

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[4] For physics, the search term "phys" (SCI's abbreviation for "physics") has been used in the address field, which neglects some expressions for physics in other languages. For materials science & engineering the search term "mat-sci OR mat-eng*" seems more appropriate, because some departments focus on engineering rather than on science in their names.

[5] These comparisons and extrapolations need to be regarded with some caution, however. First, they do not consider the type of institutions, which will be discussed below. Second, since our method does not measure the number of institutions, but their overall strength in terms of research publications, it is important to consider co-authorship behavior. Indeed, authors from nano-institution rarely collaborate with authors from other nano-institutions but prefer authors from established disciplines, whereas physicists frequently collaborate with colleagues from other physics departments. That difference in co-authorship behavior results in an underestimate of the institutionalization strength of disciplines with a comparatively low rate of interdisciplinary collaboration.

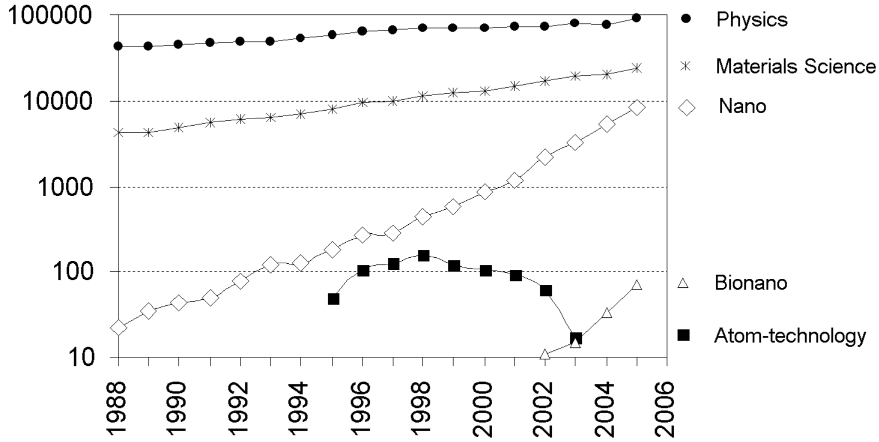


Figure 1. The institutionalization strength of nanotechnology as defined in the previous compared to the institutionalization strength of the mature discipline of physics and the relatively young discipline of materials science. The bump from around 1994 to 2003 represents the temporarily institutionalization of "atom technology" in Japan. The steep line starting about 2002 describes the recent emergence of bionano-institutions. The five curves thus represent five different states and types of institutionalization

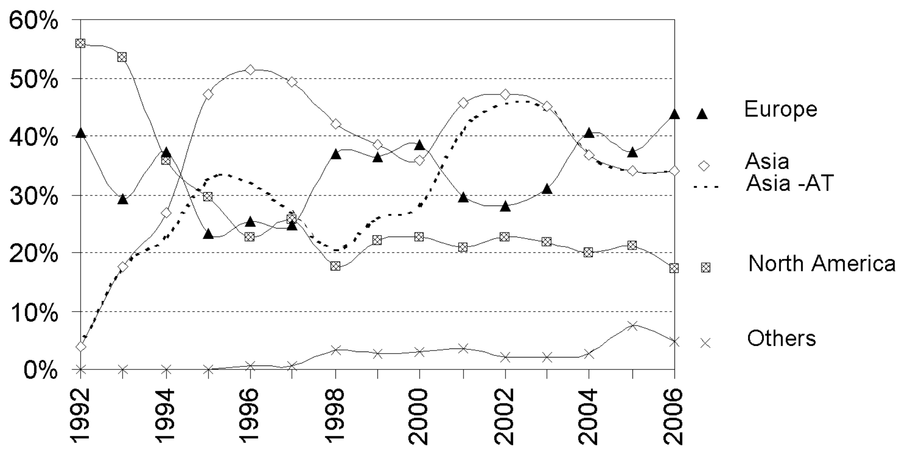
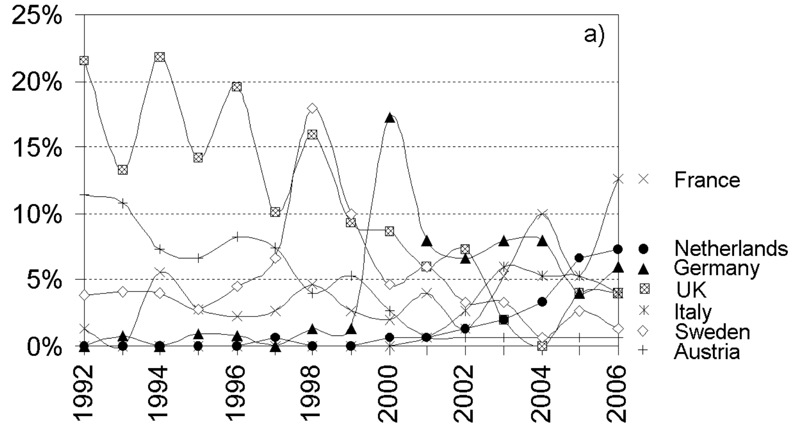


Figure 2. The relative nano-institutionalization strengths in North America, Europe, Asia, and other countries ('–AT' means without atom-technology-institutions)

The impact of a single country can be particularly high if the institutionalization is controlled by centralized science policy. An extreme example of such policy is the ten-year Atom Technology Project (ATP) in Japan, which created all of a sudden very active atom-technology-institutions that disappeared again ten years later (Figure 1).



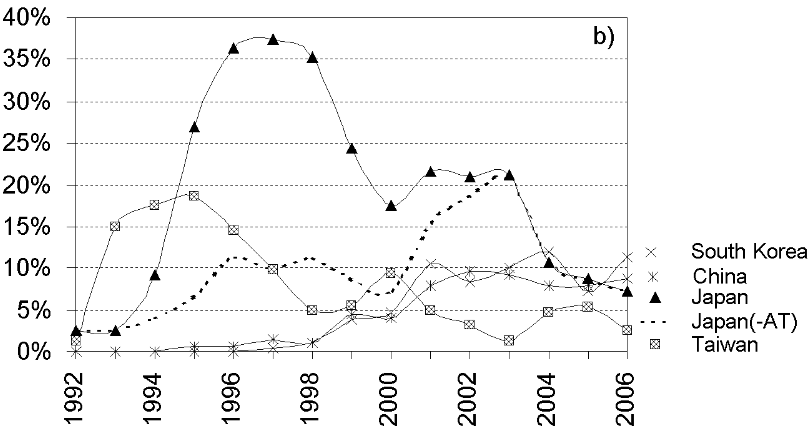


Figure 3. The global relative nano-institutionalization strengths (a) in selected European and (b) in selected Asian countries ('–AT' means without atom-technology-institutions)

A breakdown of the relative institutionalization strengths by geographical regions (Figure 2) provides a first idea of the fluctuations behind the seemingly steady dynamics. It illustrates, for instance, that in the mid-1990s the relative institutionalization strength sharply declined in North America (then exclusively the

US), and sharply rose in Asia (then exclusively Japan and Taiwan). The bump of the ATP in Figure 1 returns in the form of a smooth but distorted bump of the Asian curve in Figure 2, revealing along with the second smooth bump the impact of strong governmental control on the process. Compared to the Asian and, since 1999, also to the US curve, the European curve has always been strongly fluctuating around an average share of about a third. That is because in Europe many countries have been involved with different relative institutionalization strengths at different times (Figure 3a). Unlike the US and the individual Asian countries involved (Figure 3b), most European countries show strong fluctuations for much of the time period, which suggest that a strong and persistent governmental control of the institutionalization has been missing there.

A brief history of the institutionalization of nanotechnology worldwide

Since the institutionalization of nanotechnology reveals a very complex geographical picture, it is useful to provide first a qualitative analysis of the development before analyzing general trends of the process in terms of the categories of discipline, research sector, and institutional type in the next section. Based on the publication activity of the nano-institutions represented in the samples, the following provides a brief history of the worldwide institutionalization process with focus on the most active nano-institutions and with considering the science policy contexts in which they emerged. Such a history of course differs from the narratives that actors in retrospect tell about the foundation of their own nano-institutions, which they frequently date back to earlier years. However, for the institutionalization of nanotechnology *research*, it is more reasonable to take the first research publication by a nano-institution as an indicator for its foundation, and to ignore all the institutional paper constructs that have never or hardly appeared in research publications.[6]

From the beginning to 1999

The first nano-research institution that made a short appearance with three papers in 1984 was a Californian company called Nanometr Inc that worked on semiconductors. Two years later, the first academic institution was established in the Department of Electrical Engineering at the University of Glasgow, a nano-electronics research group that two years later turned into a research center. In 1987 the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell University, funded by the US National Science Foundation (NSF) since 1977, was renamed into the National

[6] Because the following analysis is only based on random samples for 1995–2006, it does not correctly describe the developmpent of individual institutions in that period. Thus, many more recently established nano-institutions are missing in the following.

Nanofabrication Facility, which would become the by far most active nano-institution worldwide for many years. In 1988, the Research Development Corporation of Japan (JRDC) launched the Yoshida Nanomechanism Project in Tsukuba, Ibaraki, which also collaborated with Nikon and which remained the only Japanese nano-institution up to 1993, when RIKEN established a lab for nanoelectronics in Wako, Saitama. For most of the 1990s, however, the dominating Asian nano-institution was the National Nano Device Lab in Hsinchu, Taiwan, founded probably in the late 1980s as a lab at the National Chiao Tung University.

During the 1990s numerous nano-institutions emerged both in the US and Europe. In 1993 NSF decided to extend the National Nanofabrication Facility to become the National Nanofabrication Users Network (NNUN) that included beyond Cornell four other universities (Howard University, Pennsylvania State University, Stanford University, and University of California at Santa Barbara). However, much more active nano-labs and centers were established independently at other universities, including the University of Cincinnati, Texas A&M, University of Kentucky, University of Minnesota, Princeton University, and Rice University, where Richard Smalley founded what ultimately became the most active nano-center in the US. In contrast to universities, the many and huge governmental research institutes in the US showed no interest in nanotechnology during the 90s, with the exception of an active US Navy lab in Washington DC. According to the appearance of their publications in the samples, Sandia National Labs seems to have established a small unit only in 1999, both Oak Ridge National Lab and the NASA Ames Research Center in 2002, Lawrence Livermore National Lab in 2003, and Argonne National Lab in 2005, but all their publications never grew to a remarkable number. On the other hand, since the mid-1990s many start-ups with nano-names emerged from US universities. They were so actively involved in research that from about 1996 to 2002 their publications made about a third of all publications by US nano-institutions.

In Europe, the institutionalization of nanotechnology in the 1990s was clearly driven by universities, and mostly by departments of electrical engineering. Particularly UK universities founded new nano-labs and centers, including the universities of Warwick, Birmingham, Greenwich, and Cambridge (Figure 3a). Apart from two active surface science labs in Lyon and Montpellier in France, most other nano-institutions at European universities emerged in smaller countries, like two departments in Austria at the Agricultural University in Vienna and the University of Graz, which together made Austria the second strongest nano-institutionalized country in Europe for most of the 90s, and in Sweden in Göteborg and Lund, which even dominated the European scene for a short time. Also some Central and Eastern European countries established nano-institution in the mid-90s, particularly the Masaryk University in Brno, Czech Republic, the St Petersburg State University in Russia, and the Hungarian Academy of Science. In contrast to the US and even more so to Asia, European governments discovered nanotechnology only lately. The first, and for several years the only, nano-lab at governmental research institutes in Europe was established at the Paul Scherer Institute in Switzerland in 1994. Three years later, the Spanish National Research Council (CSIC) financed a nano-lab in Madrid. Only in 1999, the Research Center Karlsruhe (FZK) in Germany, which was then still remodeled from an obsolete huge nuclear energy research center, created a big nanotechnology institute in cooperation with the local university, which almost single-handedly led to the steep rise of Germany in Figure 3a. Apart from a few start-ups, that was the first publishing nano-institution in Germany and would soon become the most active one in Europe.

For most of the 1990s, nano-institutions in Asia were confined to Taiwan and Japan (Figure 3b), and both countries strongly focused on governmental research institutes. Under the direct control of the Taiwan National Science Council, the National Nano Device Lab in Hsinchu rapidly grew in the early 1990s and was for some time even the most active nano-institution worldwide. Yet, because it remained the only Taiwanese nano-institution up to about 2003, when the first nano-centers were created at universities in Chungli, Taipei, and Taichung, Taiwan could not keep up with the global institutionalization speed of nanotechnology. In Japan, the development was much more complicated. In 1993, RIKEN's nano-electronics lab replaced the earlier nano-mechanism project by JRDC and steadily grew as the only Japanese nano-institution up to about 1996, after which its activity stagnated or even decreased. In the second half of the 1990s the universities of Tokyo, Hiroshima, Hokkaido, and Ritsumeikan established nano-centers or labs; also some nano-start-ups emerged and few companies such as Canon founded their own nano-research centers. Yet, despite these efforts by universities and companies, the institutionalization of nanotechnology appears to have lagged behind the global development. However, in 1992 the Agency of Industrial Science and Technology (AIST) of the Japanese Ministry of International Trade and Industry had founded the ten-year "Atom Technology Project" under the official title, "Research and Development of Ultimate Manipulation of Atoms and Molecules". The project was funded by about USD 250 million and located in the newly established Joint Research Center for Atom Technology in Tsukuba. Thus, the governmental institutionalization of nanotechnology in Japan almost replaced the term "nanotechnology" by "atom technology" for about ten years. That explains the seemingly discontinuous institutionalization process in Japan, and in Asia overall, during the 1990s, if we would exclude papers from atom-technology-institutions (see the dotted line in Figures 2 and 3b). On the other hand, it demonstrates the strong dependence of the Japanese institutionalization on governmental efforts.

From 2000 to 2006

Around 2000 the institutionalization of nanotechnology changed worldwide for many different reasons. A common reason in the US, Europe, and Japan, however, is that governments in 1999 began to increase their nanotechnology budgets with annual growth rates in the order of 50% for some years.

In the US, the National Nanotechnology Initiative (NNI) was launched in January 2000 by President Clinton, which included from the beginning all major federal ministries and agencies and which provided much larger funding for nanotechnology than before. Before 2000 the institutionalization of nanotechnology in the US was much slower than in Asia and Europe, such that the relative institutionalization strength had dropped from 56% in 1992 to 18% in 1998. The NNI indeed stopped the rapid relative decline already in 1999, when it was announced by a public campaign, and in the following years nano-institutions grew in the US almost at global speed. There is little measurable impact on governmental research institutes, however, and rather a negative impact on the institutionalization of nano-research in industry. Instead the institutionalization of nanotechnology occurred primarily at universities. From 1999 to 2003 alone, new nano-institutions appeared, in the order of appearance in the paper samples, for instance, at the University of North Carolina, Clemson University, University of Wisconsin, Northwestern University, Rutgers State University, University of Washington, University of Connecticut, New Jersey Institute of Technology, SUNY Albany, SUNY Buffalo, University of Rochester, Virginia Polytech, University of Michigan, University of Notre Dame, Georgia Institute of Technology, University of Florida, University of Texas, University of Southern California, Ohio State University, University of Illinois, University of Nevada, University of New Hampshire, University of South Carolina, Massachusetts Institute of Technology, University of Notre Dame, University of California at Riverside, Arizona State University, and CUNY College Staten Island. The trend has continued up to today, such that more than a hundred US universities have now a nano-institution. The preferred institutional type has always been a nano-center that includes groups from different disciplines. And indeed, that is what the NNI has mainly supported. Apart from a national network of 14 user facilities, the NNI currently finances more than 50 nano-centers at universities for "multidisciplinary research among investigators from a variety of disciplines and from different research sectors".[7] Nano-labs were founded mostly in departments of electrical engineering or materials science and frequently at technical universities, and more recently even some nano-departments emerged. SUNY Albany went even a step further and established a College of Nanoscale Science and Engineering.

[7] Quoted from the NNI website at http://www.nano.gov/html/centers/nnicenters.html (accessed 15 August 2006).

Since Canada has been included in the set of North America, it should be noted that its share has always been very small compared to the US. A first nano-center temporarily appeared at the University of Toronto in 1999, but only since 2001, and probably influenced by the NNI, nano-groups, labs, or centers have been established at the universities of Montreal, Queens, Saskatchewan, Toronto, Alberta, and Calgary. In addition, the National Research Council has founded a National Institute of Nanotechnology at the University of Alberta.

In Europe, most governments discovered nanotechnology only after 2000, which was likely a side-effect of the NNI like in Canada. For instance, the original Fifth Framework Programme (1998–2002) by the European Commission did not mention nanotechnology, which was included only in 2000 in subsequent calls and reprinted brochures. Similarly national governments retroactively calculated nano-budgets for the previous years, which had not appeared in their earlier reports, and, by the same approach, created nano-budgets for the subsequent years that showed impressive growth rates. Since around 2001 the Italian National Research Council (CNR) and other governmental organizations established national nano-labs, institutes, and centers of excellence at many universities, including in Lecce, Trento, Milano, Roma, Pisa, Ferrara, Modena, Bologna, Palermo, Turin, and Trieste. In France the National Center for Scientific Research (CNRS) had temporarily funded surface science nano-labs already in the 1990s (in Montepellier, Belfort, and Paris) but established many new nano-materials labs from around 2001 on, in the order of appearance, in Belfort, Bagneux, Marcoussis, Lille, Bordeaux, Paris, Nantes, Marseille, Lyon, Troyes, and Grenoble. In addition the French Atomic Energy commission (CEA) established an active nano-lab in Grenoble. In Germany the already mentioned nano-institute at the governmental research center in Karlsruhe became already active in 1999 to be followed a few years later by a nano-institute in its former nuclear energy sister-center in Jülich. But other governmental research institutes in Germany have been reluctant to adopt “nano” in their departmental or group names. For instance, in the two relevant Max Planck Institutes of Microstructure Physics and of Solid State Physics the institutionalization of nanotechnology is still invisible in 2006 although several individual researchers are active in governmentally funded nanotechnology projects. As in other European countries, the institutionalization in Germany has occurred mainly at universities through the founding of nano-centers and departments, albeit at a lower speed than the global process. The most active country in this regard has been the Netherlands. Before 2000 there was hardly any visible Dutch nano-institution. Since then the three technical universities of Twente, Delft, and Eindhoven have established nano-groups, -labs, -centers, and -departments of steadily growing size and activity, such that the Netherlands is now, in terms of publishing nano-institutions, the fifth most active country, after the US, South Korea, China, and France.[8]

Around 2000 the institutionalization of nanotechnology changed also in Asia, because Japan reorganized its governmental research infrastructure and because new countries appeared on the stage. Even before the Atom Technology Project ended, Japan's main governmental research organizations, the Japan Science and Technology Corporation (JST) and the Agency of Industrial Science and Technology (AIST),[9] created many new nano-labs, projects, centers, and departments, most of which were located in large national research institutes in Tsukuba, the home of the Atom Technology Project. At the same time, several universities established new nano-labs and centers, such as Meijo, Osaka, Toyo, Kagoshima, Tohoku, Kyoto, Nagoya, and Kwansei universities and the Japan Advanced Institute of Science and Technology. Despite these temporary efforts, Japan held a global share of about 20% of nano-institutions activity only up to 2003 after which that dropped down to 7%.

In the late 1990s, China and South Korea began their institutionalization of nanotechnology from virtually nothing to the global top three, both at about the same speed and with similar patterns at the beginning. In China, the Qingdao Institute of Chemical Technology (now, Qingdao University of Science and Technology) had a nano-center already in 1995, but that remained the only one of its kind for several years. Since 1999 numerous nano-institutions have been established at Chinese universities, including, by the order of appearance, Beijing University, Tsing Hua University (Beijing), University of Science and Technology of China (Hefei, Anhui), Hong Kong University of Science and Technology, Shanghai Jiao Tong University, University of Hong Kong, Xiamen University, Capital Normal University (Beijing), Wuhan University of Science and Technology, Nanjing University, Changchun University of Science and Technology, China Normal University (Shanghai), Sichuan University, Shandong University, Nanjing University of Aeronautics & Astronautics, and Tongji University. Several of these nano-institutions have become "key labs" of the National Ministry of Education since about 2002. In stark contrast to Japan, China did hardly establish purely governmental nano-institution, with the exception of an early research center of nanocrystalline alloys at the Central Iron and Steel Research Institute (Beijing) and several smaller nano-units in the Chinese Academy of Science (Beijing) that recently merged to become the National Center of Nanoscience and Technology.

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[8] The Dutch institutionalization process shows some peculiarities, because the Institute of Nanoscience at Delft is funded by the US based Kavli Foundation and because Twente's huge Institute of Nanotechnology grew out of the MESA institute, established already in 1990 largely for electrical engineering, by integrating increasingly more disciplines. I am grateful to Arie Rip for useful information and comments on an earlier draft of this paper.

[9] Part of a larger reorganization of Japanese research agencies, both organizations later changed their names: AIST became the National Institute of Advanced Industrial Science and Technology in 2001, and JST the Japan Science and Technology Agency in 2003.

As the first and for two years the only nano-institution in South Korea, the Nanoelectronics Institute at the Seoul National University appeared in 1997. Like in China, universities began to establish nano-institutions since about 1999, such as, in the order of appearance, in the Korea Advanced Institute of Science and Technology (Yusong Gu), Yonsei University (Seoul), Sejong University (Seoul), Silla University (Pusan), Sungkyunkwan University (Suwon), Chungju National University, Sunchon National University, Hanyang University (Seoul), Chonbuk National University (Chonju), Kyungpook National University (Taegu), Chung Ang University (Seoul), Daegu University (Kyungpook), Kwangju Institute of Science and Technology (Kwangju), Ewha Womans University (Seoul), Pohang University of Science and Technology (Pohang), Ajou University (Suwon), Pusan National University (Pusan), Korea University, (Seoul), Soongsil University (Seoul). It seems that most major universities now have a nano-institution frequently at the institute or department level. Unlike China, however, many governmental research institutes have established nano-institutions since about 2003, including the Korea Institute of Science and Technology, Korea Research Institute of Standards and Science, Korea Institute of Industrial Technology, and Korea Basic Science Institute. In addition, some companies have now a nano-research institution, like the Samsung Advanced Institute of Technology. These concerted efforts have made South Korea within a few years the second most active country worldwide in 2006, in terms of publications by nano-institutions, but it appears that it could soon reach a capacity limit.

A few other Asian countries have recently started the institutionalization of nanotechnology, particularly Singapore and more recently India, Thailand, and Malaysia. However, with the temporary exception of Singapore, their level has been very low and all efforts seem to have come from universities thus far. Outside of Asia, Europe, and North America, only four countries have started noticeable efforts already since the late 1990s: Australia, New Zealand, Brazil, and Israel. Australia had a semiconductor nanofabrication facility as early as 1997 at the University of New South Wales (Sydney), which seems to have shortly been called the National Facility, before it disappeared when other nano-labs, -centers, and -institutes were established at the universities of Melbourne, Queensland, Wollongong, and the University of Technology in Sydney. New Zealand's University of Canterbury had a nano-group in 1998 which in 2002 merged with the Victoria University of Wellington to form a very active nano-institute. Brazil started in 1998 with two nano-labs in the governmental technology center CETEC (Belo Horizonte, Minas Gerais) and in the Universidade Estadual de Campinas (São Paulo), but the institutionalization process seems to have stagnated since several years. In Israel, a few nano-start-ups appeared already in the late 1990s, before Ben Gurion University established a nano-center around 2001 to be followed by a nano-institute at Tel Aviv University and a center at Bar Ilan University.

Overall, these four countries could reach a global share of the institutionalization strength of 7% in 2005 and, with the exception of Brazil and a few start-ups, their nano-institutions have been only at universities.

Patterns of institutionalization

Disciplines involved in the institutionalization at universities

Nowadays the term "nanotechnology" comprises many of diverse research fields in which virtually every classical science and engineering discipline has its share. That was not always so, however. Instead, the meaning of "nanotechnology" has continuously grown such that discipline after discipline defined their own nanotechnologies, which is well reflected in the history of nano-institutions.

The method used here to depict the disciplinary involvements in the institutionalization of nanotechnology is only a coarse one. On average only a third of the affiliation addresses that include nano-institutions additionally have a clear disciplinary affiliation. For instance, an author affiliated with a nano-center might include in the same byline also her affiliation with a department of chemistry. Customs differ however, as many authors and journals prefer in that case to provide two different bylines, which is not resolvable in the SCI databases. Despite this shortcoming, which reduces the data and thus creates statistical fluctuation, we may assume, however, that it does not affect the general trends (Figure 4).

At the beginning, and still for most of the 1990s, the institutionalization of nanotechnology involved mostly researchers from electrical engineering departments who mainly worked on lithography or semiconductors. The latter field has traditionally included also solid-state physicists who in the late 1990s became strongly involved in the institutionalization of nanotechnology along with other physicists working in such diverse fields as scanning probe microscopy, materials science, and opto-electronics. Despite large fluctuations physicists have been most active in the institutionalization since then, competing only with chemists (including chemical engineers). Before 2000, the involvement of chemists grew only slowly, but then steeply increased until 2002 from fields as diverse as catalysis, polymer, and nano-particles research. The subsequent temporary decline is probably due to the different disciplinary emphasis in Asia and Europe who changed the leadership twice in that time period (Figure 2). Although many of them worked in what is nowadays called nanotechnology, materials scientists and engineers became involved in the institutionalization only in 2000 and then steadily increased their share up to today. It should be noted however, that materials science and engineering is a relatively young discipline that is still much smaller than chemistry or physics (Figure 1). Moreover, as they were still struggling to define their own disciplinary identity in the 1990s (BENSAUDE-VINCENT, 2001), they were probably reluctant to blend their discipline with other emerging fields or brands, as they have indeed showed comparatively little inclination to interdisciplinary collaboration (SCHUMMER, 2004). The involvement of mechanical engineers, working for instance on MEMS and coatings, and of researchers from the biomedical fields has been low but fluctuating in the entire time period. However biomedical engineers, frequently in collaboration with electrical engineers, have been active in establishing bionano-institutions since about 2004 (see Figure 1).

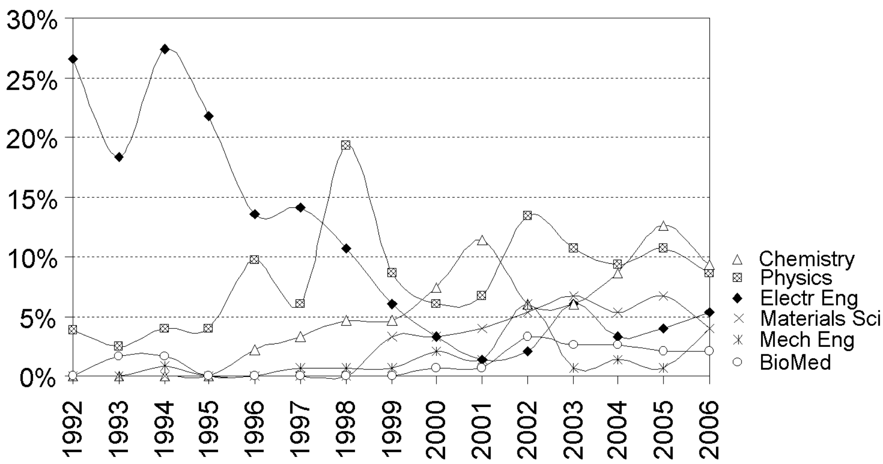

Figure 4. Disciplinary affiliations of nano-institutions (excl. atom technology)

Types of institutions at universities

There are only few global trends regarding the type of nano-institutions at universities. Despite some fluctuations, centers have been the most constant type of institution at 30-40%. Labs, once the favorite type with up to 60%, steadily declined over the years, particularly in favor of departments and institutes, which are now at 35%. The smallest institutional unit, a nano-group, grew on a lower level steadily up to 13% in 2001, after which it suddenly dropped to virtual insignificance. Programs, initiatives, projects, and the like have never played a noticeable role at universities. Thus, from a global perspective, the cross-disciplinarily model of institutionalization (represented by centers) has persisted throughout the time period, while the disciplinary model (represented by groups, labs, institutes and department) has made a steady move towards the most embedded type, the department. However, the global picture is misleading because there are tremendous regional differences (Figure 5).

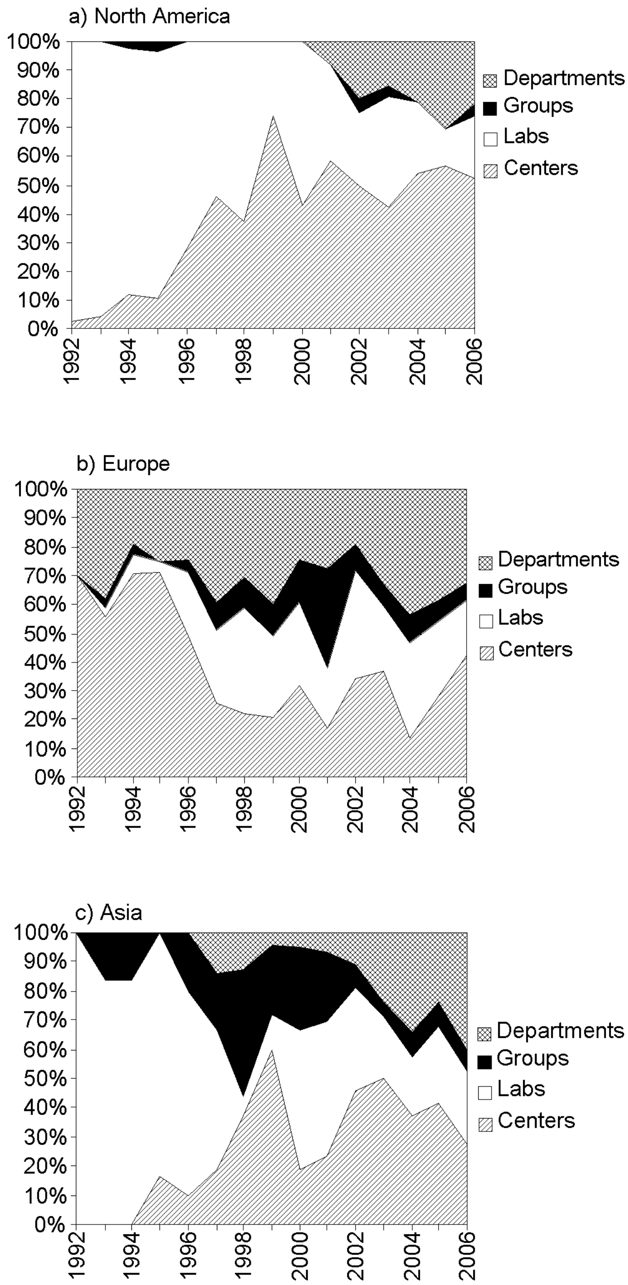

Figure 5. Distribution of the main types of nano-institutions at universities (centers, labs, groups, and departments & institutes) in North America, Europe, and Asia (excl. atom technology)

In the early 1990s, the center was the standard type in Europe, owing particularly to strong centers in the UK and Sweden. Yet, it sharply dropped there after 1997, exactly when it steeply rose first in the US and then in Asia. While it continued to be the standard model in the US (after a peak in 1999) at 50-60%, it declined again in Asia, when Europeans slowly rediscovered the center. The strong fluctuations of centers in Asia and Europe suggest that, unlike in the US, centers are considered rather a temporary form than a model of permanent cross-disciplinary institutionalization. Labs, which never played a big role in Europe, were the former standard model both in the US and Asia. In the US, where the unique "facilities" have been included in the category of labs, most labs were obviously remodeled into centers by 2000, when the NNI was distributing large sums exactly for nano-centers. In Japan many nano-labs must have been remodeled into nano-groups, some also into departments, during the Atom Technology Project (ATP). It is likely that they did not receive much of the centralized ATP funding and thus institutionalized quite early at the lowest disciplinary level of groups. The sudden drop of groups in favor of departments in Asia in 2002 suggests that the institutionalization process has made a strong move towards deeper disciplinary institutionalization. In the US, where nano-groups have been virtually inexistent, departments have grown out of labs only since 2000, but the share is still comparatively low.

In Europe, the mixture of nano-institutions has, after 1997, not experienced such dramatic changes as in the US and Asia. That is in part because more countries with different science policies are involved, such that national differences and changes are leveled out. However, it is striking that institutes and departments have constantly played a considerable role since the early 1990s. At the beginning these were only a handful of early established and very active departments in Sweden, Switzerland, and Austria. They hardly found imitators in their own countries, but they might have become early models of the disciplinary institutionalization in other European countries. Although patterns differ between European countries, the prevailing institutionalization process seems to begin either with a center (as a loose association of researchers from the same discipline or not) or a group, out of which an institute or department emerges. As long as nanotechnology flourishes, new centers continuously emerge that step-by-step turn into departments, overall providing a rather constant share of all types of institutions.

That disciplinary institutionalization model is more recently also obvious in Asian countries, particularly in China and South Korea. In contrast, the typical US nano-center is bigger and more multidisciplinary and almost completely funded and inspired by the NNI for a limited time period. It is likely that this model of the cross-disciplinary institutionalization persists only as long as the center is funded. The relative strength and dynamics of the institutionalization process in Europe, Asia, and North America (Figure 2) further suggests that the disciplinary model is also more successful than the cross-disciplinary model, in terms of the number and research activity of nano-institutions.

The share of governmental and industrial research institutions

Globally, nano-institutions at universities have always been the most numerous and active ones in terms of publications in research journals. However, there are important regional differences in the share of governmental and industrial research institutions in the institutionalization of nanotechnology.

Since for industrial research institutions the primary publications are patents rather than journal papers, the SCI database is not an ideal source for studying the industrial institutionalization of nanotechnology. However, even if the absolute numbers are misleading, we may compare the relative share of industry in different regions at different times. An industrial nano-research institution is here defined by the inclusion of the prefix "nano" it its address details. This can be anything from a small start-up company called "Nanomaterials Inc" to a huge company that in its research labs has a division for electronics with a sub-unit for, say, nanoelectronics. A simple measure for the size of the company is the place where "nano" occurs in the author's address. Thus, "Nanomaterials Inc" would likely be a small company, whereas a sub-unit for nanoelectronics that occurs only in the forth place of the address details would rather belong to a very big company.

In the US, industrial nano-research institutions rapidly grew in the mid-1990s to about a third of all nano-institutions in terms of publications (Figure 6). Virtually all were start-ups, and many were probably founded by faculty members of universities, which the Bayh-Dole Act allowed, even encouraged. The subsequent strong fluctuations are in part due to the short lifetime of some start-ups, but many persisted, albeit with changing research activities. After the foundation of the US NanoBusiness Association in 2001, nano-research labs in bigger companies, like Motorola, began to replace the start-ups for a short time, after which research from industrial nano-institutions has almost disappeared. Compared to the US, the industrial institutionalization of nanotechnology in Asia and Europe is almost insignificant. Apart from a few start-ups in both regions over the entire time period, there was a brief intermezzo in Asia only around 1998 when some bigger companies, particularly Canon, had a nano-research center. Following-up the foundation of the European NanoBusiness Association in 2002, also a few bigger European companies, like Infineon and Thales, had publishing nano-research units for a brief time. Since then industry has almost disappeared. Whether industrial nano-research institution moved from journal papers to patents or disappeared altogether is difficult to say from the data. At least they stopped collaborating with universities in public research, as they had done before, and thus lost impact on the public institutionalization process of nanotechnology. That impact, and its subsequent disappearance, was strong only in the US.

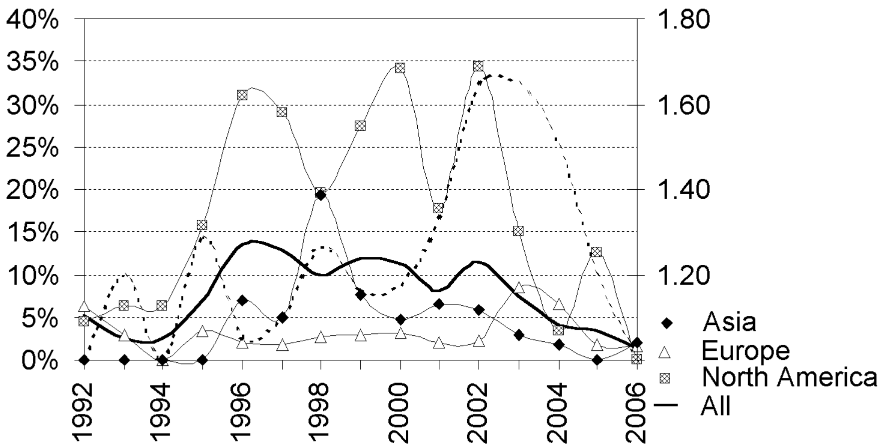

Figure 6. Relative nano-institutionalization strength of industrial research institutions (compared to universities and governmental research institutes) each in North America, Europe, and Asia (excl. atom technology). The dotted line is a measure of the average size of the companies (right axis) according the method described in the main text

To complete the picture, we must finally consider the share of governmental research institutes in the institutionalization of nanotechnology (Figure 7). Here each of the regions reveals a different pattern. In the US, the many huge governmental research labs have always been reluctant to establish active nano-institutions, which is in stark contrast to Asia, particularly to Japan and Taiwan. In fact until around 2000, nano-institutions in Asia were predominantly established and run by governments. The steady decline is a combination of two trends: the late institutionalization of nanotechnology at Japanese universities and the growing share of China and South Korea that both depend mainly on universities. In Europe the overall trend was almost reverse until 2004, although science policies greatly differ among European countries. The institutionalization of nanotechnology started almost exclusively at universities. Over the entire time period only five governments have one after the other made visible institutionalization efforts in their own research institutions which resulted in an average growth with four peaks in Figure 7: Switzerland (around 1995), Spain (around 1997), Germany (around 2001), and Italy and France (around 2004). UK and Sweden, the early European drivers in the institutionalization of nanotechnology, never established research-active governmental nano-institutions; and although their universities had nano-institutions at the department level quite early, their share almost continuously decreased. On the other hand, also the Netherlands has built exclusively on universities but steadily grown since its late appearance in 2000.

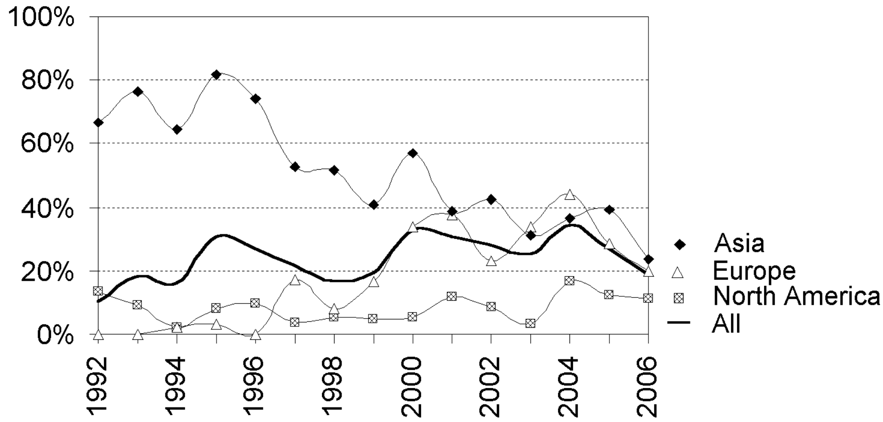

Figure 7. Relative nano-institutionalization strength of governmental research institutes (compared to universities and industry industrial research institutes) each in North America, Europe, and Asia (excluding atom technology)

Conclusions

From a global perspective, universities both started the institutionalization of nanotechnology (with a share of 85% in 1988, though at a very small level) and are nowadays the primary sector of the institutionalization (with a share of 80% in 2006 and at a very high level). Thus, it is fair to say that universities are the proper sector in which the institutionalization has taken place, whereas, despite temporary local exceptions, both industrial and governmental research institutions have been reluctant to follow. Between 1988 and 2006, governments have tried to impact that process, all by tremendously increasing their nano-budgets, but with different policies and results. Particularly Japan created very early big governmental research institutes that temporarily took over the lead but had little impact on the institutionalization at its universities, such that Japan's relative strength dropped down from 37% in 1997 to 7% in 2006. From the beginning, the US policy has counted mainly on governmentally funded multidisciplinary labs and centers at universities and could, after a steep decline in the 1990s, hold its relative institutionalization strength only by tremendously increasing its financial efforts. Its cross-disciplinary institutionalization model in the form of temporarily funded centers is likely to have little lasting effect, so that only the recently established nano-departments will probably persist once the center-funding stops. In Europe, most governments completely ignored nanotechnology before 2000, although several countries, like the UK, Sweden, and Austria, had universities with the most advanced institutionalization in the 1990s. Lacking governmental support, their relative strength steadily declined to almost zero. Starting around 2000, and likely inspired by observing the US and Japan, governments in other European countries, like Germany, Italy, and France, introduced some combination of the US and Japanese policies, i.e. some governmental research institutes plus some governmentally funded centers at universities. Whether that only combines the disadvantages of the US and Japanese policies or will have some synergetic effect on the institutionalization process remains to be seen. At least France could make a strong impact. In a few other countries, however, particularly in the Netherlands, South Korea, and China, governmental efforts have directly been focused on strengthening the institutionalization at their public universities within the existing structures, i.e., by establishing nano-departments and institutes where strong groups or centers existed before. Although these countries started lately, their policies have proved to be clearly the most successful ones in terms of the relative strength and dynamics of the institutionalization.

It is not clear, however, if all these governments with their different policies actually aimed at the institutionalization of nanotechnology in their countries. If they did, most countries would have chosen bad policy instruments and would have saved billions of dollars by choosing more efficient instruments at the appropriate time. Of course, one could argue that the early governmental activities both in Japan, with its focus on governmental research institutes, and in the US, with its focus on cross-disciplinary university centers, did not aim at permanent institutionalization but rather at temporary support of certain research. Yet, regardless of what their aims were, all the countries discussed in this paper have collectively induced with their policies an unprecedented global institutionalization dynamics (Figure 1) that is long out of control of individual governments. For instance, if in 2006 the US suddenly closed all its university centers and simultaneously Japan all its governmental research institutes, that would altogether affect only about 11% of the institutionalization strength worldwide. The global institutionalization dynamics is so strong that such a closure would be compensated for by new nano-institutions in less than three months. Moreover, whereas in the beginning nanotechnology at universities was largely confined to the discipline of electrical engineering, governments have broadened the meaning in their nano-budgets to include now most of the classical science and engineering disciplines. Despite their less than optimal instruments, governments have thus induced a social dynamics that is about to affect deeply the entire institutional structure of universities. While most governments have been unable or unwilling to institutionalize nanotechnology in their own research institutes at the same speed, it is unclear why they have focused their efforts particularly on institutes of higher education, and how that will affect the future of education. All in all, it rather looks like a social experiment that has run out of control.

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