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Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology

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This paper first describes the recent development that scientists and engineers of many disciplines, countries, and institutions increasingly engage in nanoscale research at breathtaking speed. By co-author analysis of over 600 papers published in "nano journals" in 2002 and 2003, I investigate if this apparent concurrence is accompanied by new forms and degrees of multi- and interdisciplinarity as well as of institutional and geographic research collaboration. Based on a new visualization method, patterns of research collaboration are analyzed and compared with those of classical disciplinary research. I argue that current nanoscale research reveals no particular patterns and degrees of interdisciplinarity and that its apparent multidisciplinarity consists of different largely mono-disciplinary fields which are rather unrelated to each other and which hardly share more than the prefix "nano".

1. Introduction

BRAUN et al. (1997) analyzed the early growth of nanoscience and nanotechnology during the period 1986–1995 by counting the occurrences of the prefix "nano" in the titles of scientific papers. They found exponential growth with the remarkable doubling time of 1.6 years. Furthermore, their title word analysis allowed to delineate the main research topics then (i.e., nanocrystals, nanoparticles, nanocomposites, nanoclusters, and nanotubes) as well as their respective trends, giving the impression of a rapidly emerging and rather clearly defined research field in which mainly physicists and chemists are involved.

In the mid-1990s, governmental funding of nanoscale research was so low that most countries did not even consider an extra-budget for this field. Since about 1999, however, the situation has changed drastically. While research has continued to grow at high speed (see Section 2), also governmental funding has grown exponentially, with, in this area, extraordinary doubling times of less than two years in the US, Japan, and Europe (NRC, 2002; KHOSLA, 2002; BMBF, 2002). In absolute figures, the US, Japan,

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and Europe have spent for nanoscale research US$ 604 million, US$ 580 million, and EUR 439 million, respectively, in 2002. Nowadays, no country wants to lag behind in a race for what is expected to become a revolutionary technology. The US National Science and Technology Council promises (NSTC, 2000): "The effect of nanotechnology on the health, wealth, and lives of people could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century." Compared to the early period analyzed by BRAUN et al. (1997), nanoscale research has become increasingly driven by science policy.

Science policy makers cherish particular hopes in interdisciplinary nanoscale research, such that there is literally no report that does not point out the need of interdisciplinarity,* as there is no funding program that does not explicitly address inter- or transdisciplinary approaches. At the same time, definitions of nanoscience and nanotechnology, frequently no longer distinguished from each other, are extremely vague. Since almost every material object has one or the other characteristic molecular or crystallographic length in the 1-100 nanometer range, as most definitions require,** almost every modern science and technology concerned with materials might qualify as nanoscience or nanotechnology. Given the tremendous amounts of governmental funding, the vagueness of definition and the lack of reference to particular disciplines create new space for interdisciplinary research.

The main goals of this paper are to study the degrees and patterns of multi- and interdisciplinarity in this new space of current nanoscale research and to investigate research collaboration between different institutions and between different geographical regions. Section 2 first describes the hype-like growth of using the prefix "nano" in papers of various disciplines since 1995, which requires careful conceptual and methodological consideration in Section 3: about how to define the scope of nanoscale research; about an adequate scientometric approach to measure multi- and interdisciplinarity; about disciplinary categories; and about adequate measures and indices. In addition, I suggest a new approach to visualize both quantitative degrees and qualitative patterns of multi- and interdisciplinarity in Section 3.5. Section 4 provides the analysis and interpretation of data obtained from co-author analysis of more than 600 papers published in 2002 and early 2003. By comparing the results with those of a

* For a report that formulates that need even in its title, see MALSCH, 1997a.

** For instance, the NSET defines nanotechnology as "Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size." [http://nano.gov/omb_nifty50.htm] reference set of 100 papers from classical disciplinary research, I discuss the differences and correspondences between current nanoscale research and classical disciplinary research with references to the various indices, measures, and patterns introduced in Section 3. Besides the general pictures on interdisciplinary, interinstitutional, and intergeographic collaboration, I draw many specific conclusions, such as about each discipline's specific inclination towards interdisciplinarity and towards research collaboration with industry; about geographical preferences of interdisciplinary research; and about geographical differences in the multidisciplinary composition of nanoscale research. Finally, since the analysis allows distinguishing between different kinds of interdisciplinarity and their underlying social dynamics, I conclude with some speculative prospects about future developments.

2. The growth of "nano-title-papers"

Following up the study of BRAUN et al. (1997), this section briefly describes the growth of the occurrence of the prefix "nano" in titles of scientific papers of various disciplines from 1995 to early 2003. Table 1 illustrates some of the most frequently used "nano-terms". For brevity reasons, I call papers that include "nano-terms" in their title "nano-title-papers". Many different bibliographic databases are searchable online now and allow fast collection of data. Since in scientific discourse "nano" simply means 10^{-9} that can be prefixed to all kinds of measures other than length, which nanoscale research is supposed to be only about, database searches require some preventive steps to filter out misleading terms such as "nanosecond" (frequently used in pulse-spectroscopy), "nanokelvin" (in low-temperature physics), "nanogram" or "nanomolar" (analytical chemistry).

Table 1. The most frequently used "nano-terms" in "nano-title-papers" indexed by *Chemical Abstracts*[1]

nanoparticle	nanometer	nanophase	nano-TiO_2
nanocomposite	nanopowder	nanolithography	nanogranular
nanocrystal	nanofiltration	nanopowder	nanocapsule
nanostructure	nanowire	nanofabrication	nanoceramic
nano-sized	nanoindentation	nanomaterial	nanomachining
nanocluster	nanoporous	nanosphere	nanotribology
nano-scale	nanotechnology	nano-oxidation	nanofilm
nanotube	nanofiber	nano-electrospray	nanoelectronics

[1] Extracted by "Supplementary Term Search" of SciFinder Scholar from all "nano-title-paper" records in CAPlus; collumns in order of decreasing frequency from left to right; total number of nano-prefixed terms were 158 as of June 2, 2003.

Figure 1 present the relative growth of "nano-title-papers" in various bibliographic databases, i.e. the increase of the proportion of "nano-title-papers" of all papers. Table 2 provides further description of the databases as well some growth characteristics such as annual growth rates, doubling times, and the (fictionally) extrapolated 100%-year in which all the papers would become "nano-title-papers". If one takes the *Science Citation Index* as representative of all the sciences, although chemistry is somewhat underrepresented, the proportion of "nano-title-papers" has exponentially been growing since 1985 to about 1.2% in mid-2003 at an average annual growth rate of about 34%, which means doubling every 2.35 years. Since the mid-1990s the speed has slowed somewhat down to an annual growth rate of about 25% (doubling time of 3.1 years).

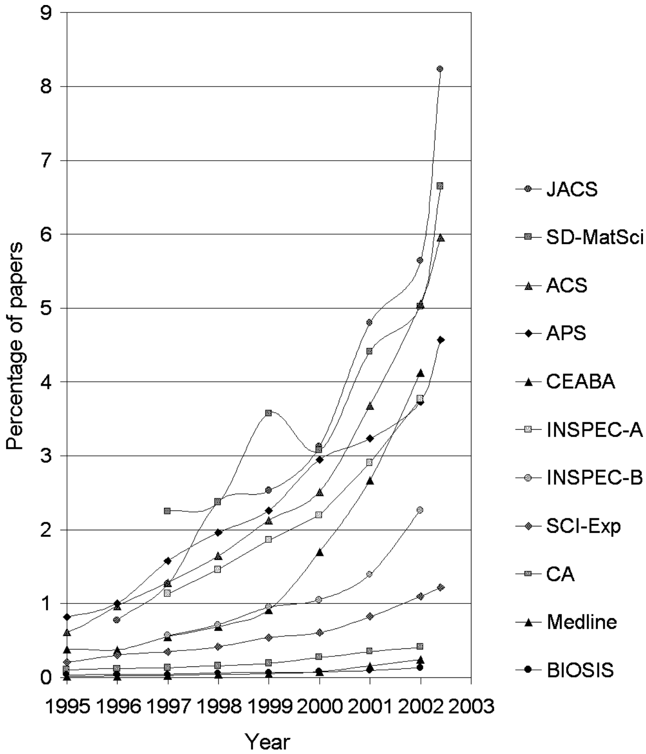

Figure 1. The growth of "nano-title-paper" in various bibliographic databases (see Table 2)

Table 2. The relative growth of "nano-title-papers" in various bibliographic databases

Database	Coverage	2002 New titles overall	2002 "Nano-titles" (%)[l]	1997–2002[m] Rel. growth rate (%)	1997–2002[m] Doubling time (years)	100% year
SCI-Exp[a]	all sciences	975,005	1.10	25.4	3.1	2022.2
CA[b]	chemistry	630,453	0.41	27.2	2.9	2024.8
Medline[c]	medicine, pharmacy & biology	484,404	0.24	56.8	1.5	2015.6
BIOSIS[d]	biology	332,939	0.13	23.0	3.4	2034.4
INSPEC-A[e]	physics	147,090	3.77	26.6	2.9	2016.0
INSPEC-B[f]	electrical & electronics engineering	72,793	2.26	29.5	2.7	2017.2
SD-MatSci[g]	materials science	38,716	5.02	17.8	4.2	2020.4
CEABA[h]	chemical engineering & biotechnology	11,832	4.12	52.4	1.6	2009.7
ACS[i]	chemistry	21,950	5.06	30.9	2.6	2013.3
APS[j]	physics	13,808	3.73	19.0	4.0	2020.7
JACS[k]	chemistry	2,645	5.60	32.3	2.5	2012.1

[a] *Science Citation Index Expanded*, all documents; [b] *Chemical Abstracts*, journal papers only; [c] *Medline-Advanced* (Silverplatter), journal papers only; [d] *Biological Abstracts*, journal papers only; [e] *INSPEC* Section A (pure and applied physics, incl. about 19% materials science), journal papers only; [f] *INSPEC* Section B (electrical & electronics engineering), journal papers only; [g] *Science Direct* "Material Sciences", journal papers only; [h] Chemical engineering and biotechnology bibliography by DECHEMA, includes *Chemical Engineering Abstracts* (CEA) and *Current Biotechnology Abstracts* (CBA), journal papers only; [i] American Chemical Society, papers of all journals; [j] American Physical Society, papers of all *Physical Reviews*; [k] *Journal of the American Chemical Society*; [l] Title word search with 'nano*' and, as far as database allows, NOT 'nanosec*', 'nanogram*', 'nanomol*', 'nanokelvin', 'nanohm', '$NaNO_3$*', '$NaNO_2$*', etc.; [m] Based on the linear regression of the logarithmic values of the percentage of new "nano-titles" for the period 1995–2002.

In 2002, scientists published 10,600 "nano-title-papers", which is no longer a marginal phenomenon. If the trend were to continue, all of our scientific papers would include the prefix "nano" in 2022!

The current proportions of "nano-title-papers" and their annual growth rates differ from discipline to discipline. In the largest and broadest disciplines – chemistry and biology, covered by *Chemical Abstracts* (CA) and *Biological Abstracts* (BIOSIS) – the overall proportion is still as low as 0.4% and 0.13%, respectively, with growth rates similar to the general trend, however. Much higher current proportions of "nano-title-papers", although at different growth rates, are produced by smaller disciplines like physics, electrical engineering, chemical engineering, and materials science. While the proportions have been long and steadily growing in physics and electrical engineering at average annual growth rates of 25-30%, chemical engineering started only in the late

1990s from a low level with tremendous growth rates of more than 50%, which is topped only by recent developments in medicine. In contrast, the relatively young discipline of materials science has had both the highest proportions and the lowest as well as the most fluctuating growths rates.

Both the American Physical Society (APS) and the American Chemical Society (ACS) publish a bunch of highly recognized journals that are supposed to cover the full spectrum of their corresponding disciplines. Thus, one would suspect that the growth of "nano-title-papers" in their journal databases is at least similar to the growth in the bibliographic database of their corresponding disciplines physics and chemistry, i.e. *INSPEC-A* and *Chemical Abstracts*, respectively. This is not the case, however. While the current proportion of "nano-title-papers" is close in *INSPEC-A* and APS (3.77% and 3.73%), it grows slower in APS than in *INSPEC-A* (19.0% as opposed to 26.6%). In contrast, while "nano-title-papers" grow at similar rates in *Chemical Abstracts* and in ACS (27.2% and 30.9%), the current level in ACS is 12 times higher (5.06% as opposed to 0.41%). Given the high international regard of their journals, it is likely that both the APS and the ACS set trends of their corresponding disciplines to be followed by others later on. This suggests that the relative growth in physics will slow down somewhat in the near future, whereas the whole of chemistry will catch up much with "nano-title-papers". Further evidence for this hypothesis comes from the flagship of the ACS, the *Journal of the American Chemical Society* (*JACS*), which currently shows the highest proportion of "nano-title-papers" of all the databases, 5.6% in 2002, and 8.2% for the period from January to June 2, 2003. If this remarkable trend continues, we would in fact see journals like *JACS* publishing nothing else than "nano-title-papers" in less than ten years!

The relative growth of "nano-title-papers" simply measures the terminological usage of scientists. As such it is likely to be the most tremendous change in the history of recent science, both regarding its speed and its wide, cross-disciplinary distribution. The crucial question still is: Does the terminological change reflect a change in scientific topics and approaches, or is it only hype such that "nano" has become a buzz word which otherwise would be replaced with scientific standard terminology without change in meaning? The fact that most materials have characteristic molecular or crystallographic lengths in the nanometer range – formerly measured in Ångströms (1 Ångström = 10^{-10}m) or microns (1 micron = 10^{-6}m) – suggests that there is much room for hype. Yet, behind hype there is frequently also a change at a more substantial level, though slower and less obvious. The present study leaves open the crucial question to which extent the raise of "nano" indicates hype or substantial change and, therefore, does not consider "nano-title-papers" a defined category of a scientific research field.

Instead, I take the remarkably broad, cross-disciplinary usage of "nano" as a starting point. If almost all the disciplines of science and engineering widely use "nano" at tremendous growth rates to describe their research topic, one would expect that nanoscale research is characterized by high degrees of interdisciplinarity, as those who try to direct research at the political level indeed hope for. The present study investigates if such expectations are justified. However, before so doing, some methodological and conceptual reflections are necessary.

3. Methodology

3.1 The scope of nano scale research: "nano-journal-papers" versus "nano-title-papers"

Every bibliometric study must first define the scope of papers to be analyzed according to clearly defined categories. Because of the vagueness of current definitions of nanoscale research, external information-based classification of papers is problematic (see Section 1). Syntactical categories, e.g. the occurrence of certain catch words like "nano", can provide a first approximation, but might easily lead astray if they refer to buzz words used without much meaning (e.g. MEYER et al., 2001). In such a situation, using categories based on the internal classification of papers by the scientific community itself is a better approach. Unlike information-based external classification, internal classification refers to the social institutionalization of a field, such as the establishment of topic-specific journals.

The launch of a new journal in a research field usually marks an important step towards the institutionalization of the field. In 1990 the UK based Institute of Physics launched its journal *Nanotechnology* as the first journal explicitly devoted to "nanoscale science and technology" with particular emphasis on the "interdisciplinary nature" of research papers. If one takes the occurrence of the prefix "nano" in journal titles as indicative, 8 further "nano journals" have appeared since then, of which 5 were new and 3 the product of re-naming older journals (see Table 3). One journal (*Nanostructured Materials*, 1992-9) disappeared again by being incorporated into a pair of established journals (*Acta Materialia* and *Scripta Materialia*) and two journals have failed to make a significant start up to now (*Journal of Metastable and Nanocrystalline Materials*, since 2000; *International Journal of Nanoscience*, since 2002). In addition, at least three further journals are announced to be published soon.*

Currently there are eight "nano journals" (see Table 3) indexed by *Science Citation Index* that include the prefix "nano" in their titles and refer to nanoscale science and/or technology in their Scope-and-Aims section. In order to draw a representative sample of current nanoscale research, these journals provide a better source than "nano-title-papers". For, unlike the authors' free choice to use the prefix "nano" in their titles, a paper published in a "nano journal" must pass a topical review according to the internal standards of the scientific community. Of course, publication in one of these journals is neither necessary nor sufficient to be counted as nanoscale research. It is not sufficient because some of the journals explicitly combine other fields with nanoscale research. And it is not necessary because many other established journals publish papers that are more or less considered belonging to nanoscale research. However, opinions differ considerably. If one compares, for instance, the two regularly updated electronic bibliographies that each try to cover all publications in nanoscale research,** there is so little agreement between both that their selection criteria appear too arbitrary or too one-sided to make it the basis of a serious study. Therefore, "nano journals" are still the best source for representative samples of nanoscale research.

Nonetheless, a comparison between papers published in the eight "nano journals", called "nano-journal-papers" in the following, and "nano-title-papers" is instructive regarding the problems of purely syntactical categories. Of the 10,691 "nano-title-papers" covered by SCI in 2002 less than 500 were published in the eight "nano journals". On the other hand, more than 50% of the "nano-journal-papers" do not contain "nano" in their title such that they would not appear in "nano-title-paper" samples. Although there is a significant correlation, it is not as strong as one might have expected. Furthermore, the mentioning of "nano" in paper titles considerably differ from "nano journal" to "nano journal" (Table 4) and, as we will see, from discipline to discipline.

* The journals in the pipeline are *IEEE Transactions on Nanotechnology*, *IEEE Transactions on NanoBioscience* and *Journal of Computational and Theoretical Nanoscience* (by American Scientific Publishers).

** *Virtual Journal of Nanoscale Science & Technology* [http://www.vjnano.org/nano/] & *Nanojournal.org* [http://www.nanojournal.org/]

Table 3. Description of "Nano Journals"

Journal name	Abbreviation	Publisher	Published (under the title) since	Scope according to self-description
Nanotechnology	*Nanotech*	Institute of Physics, UK	1990	"nanoscale science and technology and especially those of an interdisciplinary nature"
Nano Letters	*Nano Let*	American Chemical Society, USA	2000	"fundamental research in all branches of the theory and practice of nanoscience and nanotechnology"
Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures	*JVCT-B*	American Vacuum Society through the American Institute of Physics, USA	1991	"microelectronics and nanometer structures", with emphasis on "processing, measurement and phenomena"
Journal of Nanoparticle Research	*J Nanopart*	Kluwer, Netherlands	1999	"physical, chemical and biological phenomena and processes in structures that have at least one lengthscale ranging from molecular to approximately 100 nm", "at the intersection of various scientific and technological areas"
Fullerenes, Nanotubes, and Carbon Nanostructures	*Fullerenes*	Marcel Dekker, Inc., USA	2002	"all fields of scientific inquiry related to fullerenes, nanotubes and carbon nanostructures"
Physica E: Low-dimensional Systems and Nanostructures	*Physica E*	North-Holland / Elsevier, Netherlands	1997	"fundamental and applied aspects of physics in low-dimensional systems, including semiconductor heterostructures, mesoscopic systems, quantum wells and superlattices, two-dimensional electron systems, and quantum wires and dots"
Precision Engineering: Journal of the International Societies for Precision Engineering and Nanotechnology	*Precision E*	American Society for Precision Engineering through Elsevier	2000	"multidisciplinary study and practice of high accuracy engineering, metrology, and manufacturing [...] from atom-based nanotechnology and advanced lithographic technology to large-scale systems"
Journal of Nanoscience and Nanotechnology	*JNN*	American Scientific Publishers, USA	2001	"nanoscience and nanotechnology", "fundamental and applied research in all disciplines of science, engineering and medicine"
Journal of the American Chemical Society	*JACS*	American Chemical Society, USA	1879	

Table 4. Indicators of "Nano Journals"

Journal	Regular papers in 2002 (n_j)	Proportion (c_j)	"Nano-title"papers (%)	Papers analysed	Average number of authors $<n_a>$
Nanotech	150	0.14	59.3	105	4.71
Nano Let	281	0.26	79.3	103	4.32
JVCT-B	318	0.31	12.5	104	4.97
J Nanopart	68	0.07	84.3	51	3.84
Fullerenes	30	0.03	10.8	37	4.00
Physica E	63	0.05	24.1	79	3.17
Precision E	52	0.06	0	70	3.05
JNN	83	0.08	76.7	60	4.52
JACS	ca 2,600			100	5.01

Thus, a "nano-title-paper" sample would greatly overestimate journals like *Nano Letters* (and thereby chemistry) and neglect or underestimate journals like *Precision Engineering* and the *Journal of Vacuum Science & Technology B* (and thereby mechanical and electrical engineering). In research fields like those on fullerene, quantum wires, and quantum dots, whose significance to nanoscience is undisputed in the scientific community, a more sophisticated terminology has been developed beyond the simply usage of the prefix "nano" (cf. the journals *Fullerenes* and *Physica E* in Table 4). Therefore, a "nano-title-paper" sample would greatly underestimate just the further developed fields of nanoscale research.

The present study is based on co-author analysis of regular research papers published in early 2003 and in 2002 in the eight "nano journals" listed in Table 3. Because the number of papers published per year in each of the journals greatly varies (Table 4), small journals were fully analyzed while only random samples were taken from large journals to obtain enough data to draw significant conclusions. Overall, 609 papers were analyzed compared to a total of 1045 regular papers published in the eight journals in 2002. The focus on regular research papers excludes editorial notes, book reviews, "rapid communications", etc. as well as conference proceedings. The correction is necessary because the two apparently largest journals, *Physica E* and *Journal of Vacuum Science & Technology B*, publish so many proceedings of all kinds of conferences, with no or little relation to nanoscale research, that their overall character as research journal is questionable – indeed, their proportion of regular papers amounts only to 10% and 60%, respectively.

In order to compare and combine the results, for each journal j a normalized factor c_j was determined that describes the proportion of the journal to the entire field of nanoscale research with reference to the number of regular papers published in 2002, n_j.

$$N = \Sigma_j\, n_j\,.$$

$$c_j = n_j/N\,.$$

For each property p, the value of the individual journals p_j can be combined to describe the overall field of nanoscale research:

$$p = \Sigma_j\, p_j\, c_j\,.$$

In addition to the eight "nano journals", a random sample of 100 papers of the *Journal of the American Chemical Society* (*JACS*) of early 2003 was analyzed for reference and comparison reasons. Published since 1879 by the American Chemical Society, *JACS* is one of the leading journals in chemistry that covers the full scope of all research fields of the discipline (STANG, 2003). Despite its high proportion of nano-title-papers (see Section 2), *JACS* is a classical disciplinary journal that serves well as a point of reference for studying interdisciplinarity in nanoscale research.

3.2 Methods of measuring interdisciplinarity

There are many different scientometric approaches to measuring interdisciplinarity, each relying both on a system of disciplinary categories and a concept of interdisciplinarity. Most approaches take papers (or patents) as the subject of study and measure interdisciplinarity in terms of the co-occurrences of what can be considered discipline-specific items, such as keywords, classification headings, authors' affiliations, or citations. The general idea is that the co-occurrences of discipline-specific items in some way reveal the strength of the relationship or the exchange between the corresponding disciplines. Thus, co-word analyses count the number of the co-occurrences of discipline-specific keywords for papers, usually selected either by the authors or by journal editors. It is assumed that the more co-occurrences of such keywords there are in a given set of papers, the stronger is the relationship between the corresponding disciplines. For instance, a large subset of papers with both a keyword related to chemistry and a keyword related to physics would show a strong interdisciplinary relation between chemistry and physics. Similarly, co-classification analyses count the number of co-occurrences of discipline-specific headings, which, in contrast to keywords, are usually assigned by professional information managers and thus refer to a more systematic and broader scheme developed for a database (e.g., TIJSSEN, 1992; MORILLO et al., 2001). Instead of keywords and headings, co-author analyses count the co-occurrences of disciplinary affiliations of co-authors (e.g., QIU, 1992; QIN et al., 1997). Finally, assuming that every paper can be considered belonging to one discipline, citation analyses count citations between papers of different disciplines as links between these disciplines (e.g., PORTER & CHUBIN, 1985; TOMOV & MUTAFOV, 1996).

There is another, essentially different approach that classifies papers of a given field on the basis of the inter- and multidisciplinarity of the journals in which they are published, based on a journal classification suggested by KATZ & HICKS, 1995. MEYER & PERSSON (1998) used that approach to describe the degree of multi- and interdisciplinarity of the early period of nanotechnology by classifying "nano-title-papers" from 1991–1996. This approach is no longer suitable for nanoscale research, however, as "nano-title-papers" no longer represent the field (Section 3.1). In addition, it is difficult to understand what makes a paper multi-disciplinary if published in multidisciplinary journals like *Science* or *Nature*. Furthermore, by analyzing "nano-journal-papers", the present study will have to show at first if the self-description of the eight "nano journals", as being highly interdisciplinary, actually stands up to scrutiny. Thus, a method independent from journal classification is in need for which, at first glance, any of the four approaches mentioned above seem to be suitable.

Obviously each of the four approaches has advantages and disadvantages over the other three, partly discussed in the literature, and is suitable for some cases but not for others. For instance, co-classification analysis is superior to co-word analysis in larger, less homogeneous fields of study, because of the broader basis of classification schemes. Citation analysis runs into trouble when the disciplinary affiliations of papers are difficult to ascertain just because of their interdisciplinary nature. Co-classification and citation analyses cannot be applied to the most recent research, as they require database management and the accumulation of citations, and so on. Besides these disadvantages, however, there are more general reasons for employing co-author analysis in the present study.

The concept of a scientific discipline comprises both a body of knowledge and a social body that generates, evaluates, communicates, and teaches the corresponding knowledge, i.e. "discipline" is a combined cognitive and social category. Derived from the Latin term "disciplina", the English "discipline", as well as its equivalents in all the other European languages, particularly refer to the educational context of teaching and learning a certain body of knowledge, as manifested in curricula and textbooks. Systematic distinctions between two bodies of knowledge, which professional information managers are inclined to apply, need not necessarily distinguish between historically grown disciplines that the scientific community acknowledge as being distinct. In fact, the scientific community might clearly distinguish two disciplines from each other, although they share much of their knowledge, as it is the case, for instance, with biochemistry and molecular biology. Unlike paper and journal classifications, on which the other three approaches are based, the authors' departmental affiliations correspond to disciplines as combined cognitive and social category and as distinguished by the scientific community itself. Thus, if one wants to understand interdisciplinarity as a combined cognitive and social phenomenon, which is particularly important in such systematically ambiguous fields as nanoscale research, co-author analysis seems to be the method of choice.

Referring to authors' affiliation can also help avoid the dangers of distortions and artifacts due to inadequate classification of knowledge. While an ideal classification of our entire knowledge distinguishes between knowledge fields (disciplines) in each area with equal resolution and with categories adjusted to every new knowledge development, real classifications are necessarily limited. They may, for practical reasons, retain categories that are no longer adequate or neglect new areas that did not exist when the original classification system was established. For instance, science based classification systems are typically poor in distinguishing between different engineering disciplines, which would result in misconceptions of interdisciplinarity in engineering. Or, new, highly specialized subdisciplines, nowadays typically at the cognitive boundary of disciplines, could simply resist traditional information categories, resulting in interdisciplinarity artifacts by way of multi-categorization. Current nanoscale research, because of its vagueness of definition, might even be treated non-uniformly or varying in different classification systems. Unlike these shortcomings, reference to authors' departmental affiliation ensures that, in each area and at any time, the level of differentiation corresponds to what the scientific community itself considers distinct disciplines and what not.

Furthermore, co-author analysis puts emphasis on different aspects of interdisciplinarity than the other three methods. Co-word and co-classification analyses focus on the information of a paper and consider it interdisciplinary if it resists monodisciplinary qualification because it is either relevant to or lies between two or more disciplines. Citation analysis measures the flow of information between disciplines by way of the authors' cross-disciplinary reading. Like their concept of disciplines, these three methods analyze only the cognitive aspect of interdisciplinarity in terms of information. Co-author analysis, on the other hand, considers the social aspect of interdisciplinarity and focus on research practice instead of information. Scientific research is interdisciplinary, in this approach, if researchers from at least two different disciplines, according to their departmental affiliation, are involved. Because the scientific community has strict regulations about authorship, we can assume that in general each co-author has made a substantial contribution to the common research project documented by the paper. We can further assume that in general, though not always,* the disciplinary affiliation of co-authors corresponds to their disciplinary knowledge contribution. Thus, based on the notion that "discipline" and "interdisciplinarity" are combined cognitive and social categories, co-author analysis measures interdisciplinarity in terms of successful research interaction between disciplines.** And that is exactly the objective of the present study.

Finally, because of the current vagueness of definitions of nanoscale research, any analysis of interdisciplinarity based on information-only categories faces serious problems. If it is true that nanoscale research has become increasingly driven by science policy (Section 1), disciplinary dynamics is supposed to occur first on the social level. Therefore, co-author analysis is the method of choice to investigate interdisciplinary in nanoscience and nanotechnology at the present time.

3.3 Co-author analysis

Unlike the other co-occurrence analyses, co-author analysis requires the tedious work of collecting data directly from the papers because no existing database relates the affiliation addresses of each of the authors. In addition, categories must be established that are sufficiently general to deal with disciplinary and geographical diversities. In the present study, for each paper the number of authors by discipline, by institution, and by geographic region were collected, according to the categories in Tables 5-7. To get some information of the present state of institutionalization of nanoscale research, the number of authors affiliated to one or the other kind of "nano institution" (nano-laboratory, nano-research group, nano-center, etc.) was noted too, which, as a rule, is mentioned in addition to departmental affiliation.

* Of course, the disciplinary affiliation of an author need not match his or her disciplinary background in terms of formal training. For authors from universities, the focus of the present study, the discrepancy is estimated to be less than 10%. Moreover, because the discrepancy can have both an increasing and decreasing effect on interdisciplinarity measured by co-author analysis, it may be assumed that both effects level out each other.

** That does not mean, however, that co-authorship analysis captures all aspects of research collaboration. For a critical discussion, see KATZ & MARTIN (1997).

Table 5. Disciplinary categories

Abbreviation	Discipline
P	physics
C	chemistry
B	biomedical sciences, incl. biomedical engineering, pharmacology, pharmacy
M	material sciences and engineering, incl. special materials like ceramics, polymers, etc.
ME	mechanical engineering, incl. micromanufacturing
EE	electrical engineering, incl. electronics, microelectronics, microsystems
CE	chemical engineering, incl. process engineering
IC	information and computer sciences
TG	general technology (unresolved affiliation on the departmental level)
Oth	other sciences, mostly earth sciences, environmental science

Table 6. Institutional categories

Abbreviation	Institution
Uni	university, incl. research institutions or centers with at least a graduate program
Gov	governmental (and mainly governmentally funded) research institutions, incl. national or regional academies
Ind	industry

Table 7. Geographical categories

Abbreviation	Geographical regions
NA	North America (USA and Canada)
EU	Europe, incl. Turkey and countries of the former Soviet Union
AS	Asia
Oth	All others, incl. South & Middle America, Australia, Middle East

In most cases, disciplinary affiliation according to the categories of Table 5 can be unambiguously obtained for authors from universities by their departmental affiliation. If affiliation details in a recent paper are insufficient, an internet research usually provides the required information quickly. For authors with more than one affiliation, only the first one was noted. In some cases, when departments are organized below or above the level of the categories, e.g. "department of physical chemistry" or "department of physics and chemistry", the first noun was considered to indicate the discipline. Notwithstanding the few problematic cases, the departmental structure of universities appears to be rather stable and geographically universal, such that 94% of the 1838 university authors analyzed easily fall into the first eight disciplinary categories of Table 5. The category "General Technology", with overall only 3.2% of the authors, mainly covers authors of *Precision Engineering* from Asian universities that do not maintain an English website for further clarification, which might slightly undervalue mechanical engineering. The residual category "Others" includes less than 3%.

Authors from governmental research institutions and national academies are more difficult to deal with. On the one hand, these institutions do not really fit the concept of disciplines (Section 3.2), because they lack the educational context essential to the original meaning of the term – although the frequent change of positions between university and research institution as well as adjunct teaching positions usually establish close links between governmental researchers and universities. On the other hand, many research institutions are devoted to highly specialized research topics cross the disciplinary structure of universities and thus resist disciplinary classification according to our categories. To cope with this double-edged situation, a pragmatic decision was made, such that authors from governmental research institutions and academies were classified by the disciplinary categories only if the classification was as easy to obtain as with authors from universities, i.e., if their departmental structure corresponds to that of universities. Of the 435 authors from research institutions, which corresponds to 17.2% of all authors, about 88% could thus be categorized.

Authors from industry, overall 260 or 10.3% of all authors, were not considered in disciplinary classification because industrial research is neither structured according to scientific disciplines nor does it relate to the concept of disciplines proper. Instead, industrial authors were counted according to institutional categories of Table 6 as being different from authors from university and governmental research institutes. The separate treatment of industrial authors has the advantage that it allows analyzing the disciplines' different tendencies to collaborate with industry (see Section 4.3.1).

Compared to disciplinary affiliation, the analysis of the institutional and geographic affiliations of authors, according to the categories in Tables 6 and 7, is relatively unambiguous and easy if supported by internet research. New kinds of institutions in-between university and research institute, like inter-university research institutes, were treated as university if they offer at least a graduate program. Institutions with partly governmental funding were taken as industry if their names indicate any form of a private company or incorporation.

3.4 Interdisciplinarity measures and indices

Once data are collected according to the three kinds of categories (disciplinary, institutional, and geographic), data analysis can proceed by the same formalism each for disciplinary, institutional, and geographic collaboration and each for single journals or the whole field. This section introduces the formalism only with reference to interdisciplinary collaboration in the whole field, but it can mutatis mutandi be applied to any other kind of relationship analysis.

A general measure of multidisciplinarity of a field is the number of disciplines involved. Disciplines can be counted either on an author basis (by the number of authors of the discipline) or on a paper basis (by the number of papers in which at least one author of the discipline is involved). Since all of the following measures are paper-based, I define the Multidisciplinarity Index, $M^{.05}$, as the number of disciplines involved by authorship in at least 5% of the total number of papers:

$$M^{.05} = \text{count } [c_i] \text{ if } c_i > 0.05$$

$$c_i = n_i/N$$

with c_i being the Relative Size of Discipline i, n_i the number of papers in which at least one author of the discipline i is involved, and N the total number of papers.

Of course, the distribution function of disciplines over the relative size is a more precise, though less illustrative, measure of multidisciplinarity. To provide some idea about the distribution, I will also use the Relative Size of the Biggest Discipline, c^{Max}, as a simple, and for the present purpose quite useful, indicator

$$c^{max} = \text{Max } [c_i] \text{ .}$$

A general measure of interdisciplinary research is the relative number of papers co-authored by authors from more than one discipline. It is useful to break that down into two indices, depending on whether two or more disciplines, or three or more disciplines are involved. If N is the total number of papers, we can define two Interdisciplinarity Indices

I^2 = number of papers co-authored by authors from 2 or more disciplines / N;
I^3 = number of papers co-authored by authors from 3 or more disciplines / N.

If $n_{i,k}$ is the number of papers co-authored by at least one author of each of the disciplines i and k, we can define for all the binary combinations of disciplines a symmetric Interdisciplinarity Matrix with the specific Bi-disciplinarity Coefficents $c_{i,k}$ according to

$$c_{i,k} = n_{i,k}/N \text{ .}$$

The Interdisciplinarity Matrix contains all the essential information about which discipline collaborates with which other discipline and to what extent. In addition, the diagonal elements of the matrix with $k=i$, $c_{i,i}$, indicate the relative number of monodisciplinary authored papers of each discipline i.

Finally, we can define a measure for each discipline's inclination to participate in interdisciplinary research, the Discipline Specific Interdisciplinarity Indices, si_i:

$$si_i = \sum_{k\neq i} c_{i,k}/c_i \quad .$$

3.5 Visualizing interdisciplinarity by molecular graphs

For a given set of n disciplines, Section 2.4 defines $(n^2+5n+8)/2$ different indices and coefficients to describe the interdisciplinary structure of a field. If we take only the first eight disciplinary categories defined in Table 5, this amounts to as much as 56 numbers required to adequately describe interdisciplinarity in nanoscale research. Furthermore, if we want to compare the interdisciplinary structures of two or more fields (or journals) with each other, we need to compare two or more sets of 56 numbers. Obviously, here is a need to present quantitative data in visual form that allows grasping the characteristics of an interdisciplinary structure more efficiently – ideally at one glance. Moreover, insofar as scientometric results, i.e. quantitative data, are finally interpreted in qualitative terms, the kind of visual representation required here should also favor the development of adequate qualitative concepts.

Many kinds of sophisticated approaches to visualizing interdisciplinary structures have been suggested in the literature, including the methods of multidimensional scaling, cluster analysis, and network structuring (TIJSSEN, 1992 and literature quoted therein). Here, I suggest a much simpler method of visualizing quantitative relationships which, for obvious reasons, I call "molecular graphs". The simplicity confines molecular graphs to interdisciplinary structures with only as few disciplines and interdisciplinary relationships involved as in the present study (for examples, see Figure 4 and 5).* However, as with all forms of visualization, the benefit of simplicity is that it actually allows grasping the characteristic of disciplinary structures at a glance for which one otherwise needs as much as 56 different numbers in numerical representation.

Molecular graphs are topological representation with disciplines as knots connected to each other by interdisciplinarity relations. If one uses the same scale to represent the relative size of each discipline, c_i, by the diameter of a circle and to represent the bi-disciplinary coefficients, $c_{i,k}$, by the width of their connection bars, the resulting graph

* All molecular graphs in this paper are constructed and drawn using CorelDRAW®11.

also visualizes all the other indices defined above. If we confine the molecular graph to include only disciplines larger than 5%, the number of circles corresponds to the multidisciplinarity index, $M^{.05}$; the combined widths of all binary connections equals the binary interdisciplinarity index, I^2, and so on; and the relation between the diameter of each sphere and the combined widths of all its connections amounts to the discipline specific interdisciplinarity indices, si_i. In order to improve the comprehensibility of a molecular graph and to focus on the important information, it is useful to reduce its complexity by excluding less important information. For instance, like the 5%-limit for disciplines, one can exclude interdisciplinary connections smaller than 2% or 1%.

Figure 2 provides a simple molecular graph example of a three-disciplinary structure. Unlike the 12 numbers of the numerical representation (see caption), the graph illustrates the characteristics of the structure at a glance. Two disciplines of equally large size, A and B, are strongly connected to each other and dominate the overall structure. A third discipline, C, of much smaller size is strongly connected to B and only weakly to A. The graph thus illustrates three of four qualitatively different types of bi-disciplinary relations: strong and symmetrical (A-B), strong and asymmetrical (B-C), weak and asymmetrical (A-C), and weak and symmetrical. By comparing the diameter of each sphere with the combined widths of its connection, i.e. by regarding the intact border line of the spheres, we can easily recognize each discipline's tendency towards interdisciplinary collaboration, si_i, which increases from A to B to C. Finally, the graph also suggests certain interpretations. For instance, the smallness of C combined with its almost complete collaboration with B, reveals the typical characteristics of an auxiliary discipline.

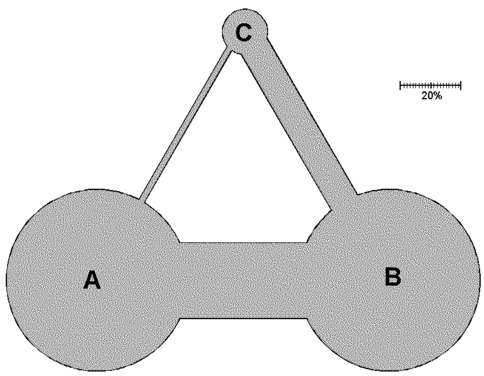

Figure 2. Molecular graph of a three-disciplinary structure ($M^{.02} = 3$, $c^{max} = 61$, $I^2 = 35\%$, $I^3 < 1\%$, $c_A = c_B = 61\%$ and $c_C = 15\%$, $c_{A,B} = 25\%$, $c_{B,C} = 10\%$, $c_{A,C} = 2\%$, $si_A = 44.3\%$, $si_B = 57.4\%$, $si_C = 80\%$)

Unlike graphs in metrical spaces, distances and positions bear no particular meaning in topological graphs. While that might appear a waste of representational capacity, the freedom of choice of distances and positions can actually be used for graphical and interpretational purposes. Because symmetrical graphs are both easier to construct and easier to grasp, it is visually advantageous to arrange molecular graphs along simple symmetrical figures with equal distances. In addition, the knots can be arranged in such a way as to minimize the crossings of their connections, which improves their visual comprehensibility. This graphical strategy automatically moves the mostly connected knots into the center of the graph. In terms of disciplines, the disciplines that collaborate with most other disciplines and that are usually the biggest in a certain field, move into the center, while smaller, less connected disciplines move to the periphery. The graphical strategy thus suggests an interpretation that distinguishes between more important and less important disciplines. As will be illustrated in Section 4.2, the graphical strategy even suggests distinguishing between patterns of interdisciplinarity, and thereby provides the qualitative concepts for our interpretation.

4. Data analysis and interpretation

4.1 Multidisciplinarity versus Interdisciplinarity

Although both terms are frequently used without much distinction, there is a fundamental difference between multidisciplinarity and interdisciplinarity (see KLEIN, 1990, pp. 56-63). A research field is multidisciplinary if many disciplines are involved, as indicated by the multidisciplinarity index, $M^{.05}$, and, more precisely, by the distribution function of disciplines over their relative size. On the other hand, research is interdisciplinary according to the definition in Section 3.2, if it includes interaction between different disciplines, as indicated by the interdisciplinarity index, I^2, and, more precisely, by the interdisciplinarity matrix. Thus, a research field can be highly multidisciplinary without being interdisciplinary, if many disciplines are participating without any interaction between them. Similarly, strong interdisciplinary research between only two disciplines does not mean a high degree of multidisciplinarity.

The difference between multidisciplinarity and interdisciplinarity, as well as the difference between coarse and fine measures, become important if we compare nano-scale research, as represented by the eight "nano journals", with data from a typically disciplinary journal such as the *Journal of the American Chemical Society* (*JACS*) (see Table 8 and Figure 3). What strikes first is that, with 5 disciplines larger than 5% ($M^{.05}$ = 5), *JACS* does not appear as monodisciplinary as one might have expected.

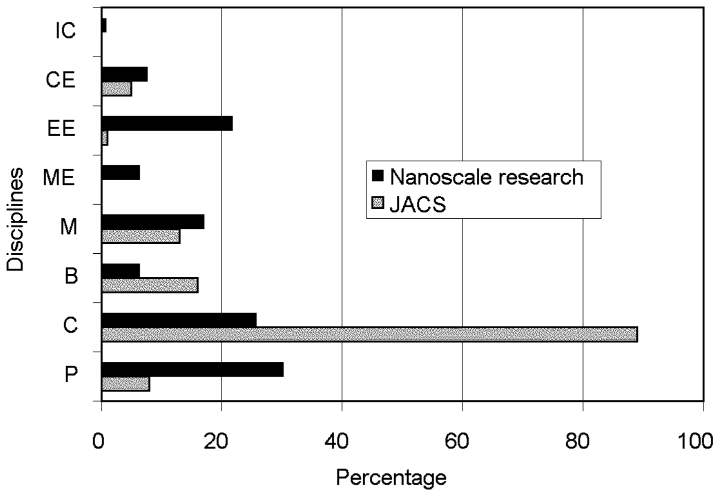

Figure 3. The relative size of disciplines (c_i) involved in nanoscale research compared to *JACS* (for disciplinary categories and abbreviations, see Table 5)

Table 8. The relative size of disciplines and multi- and interdisciplinarity indices in nanoscale research compared to *JACS*

	c_P	c_C	c_B	c_M	c_{ME}	c_{EE}	c_{CE}	c_{IC}	$M^{.05}$	c^{max}	I^2	I^3	$<n_a>$
Nano Research	30.2	25.8	6.3	17.1	6.3	21.8	7.7	0.8	7	30.2	36.5	5.7	4.42
JACS	8.0	89.0	16.0	13.0	0.0	1.0	5.0	0.0	5	89.0	30.0	6.0	5.01

In fact, classical disciplinary research is not monolithic, and it is questionable if it has ever been so as GIBBONS et al. (1994) have suggested.* By taking *JACS* as a point of reference for classical disciplinary research, we avoid attributing to nanoscale research features of allegedly novel kinds or degrees of multi- and interdisciplinarity and can focus on actual differences. Indeed, the multidisciplinarity index of nanoscale research, $M^{.05} = 7$, is not considerably higher than that of *JACS*. The striking difference is rather in the distribution function. What makes *JACS* a classical disciplinary journal is that the vast majority of its papers (89%) are (co-)authored by chemists and that the second largest discipline is as small as 16%. In contrast, the largest discipline in nanoscale research, physics, is 30.2% and shortly followed by chemistry with 25.8%.

* For examples of interdisciplinarity in the 19th-century life sciences, see SCHUMMER (2003).

In general, nanoscale research is very multidisciplinary not because of the high number of disciplines involved but because there are relatively many disciplines involved at similar size.

On average, a paper in nanoscale research is authored by 4.42 authors, which is slightly lower than an average paper in *JACS* ($<n_a> = 5.01$). In 63.5% of the nanoscale research papers, these authors are from a single discipline, which amounts to an interdisciplinarity index of $I^2 = 36.5\%$ that is only little higher than that of *JACS* ($I^2 = 30.0\%$). On the other hand, papers authored by authors of three or more disciplines are slightly more frequent in *JACS* ($I^3 = 6.0\%$) than in nanoscale research ($I^3 = 5.7\%$).

We may now draw the first and most important conclusion. Although nanoscale research is more multidisciplinary, in terms of both the number and relative size of disciplines involved, than classical disciplinary research, its degree of interdisciplinarity is only slightly higher. In other words, although nanoscale research contains many disciplines at equal rank, their research interaction is surprisingly low at the present time. If nanoscale research is something fundamentally new cross the established disciplines, then its novelty does not manifest itself in remarkably higher degrees of interdisciplinarity – notwithstanding so many hopes expressed in governmental reports, the self-descriptions of our “nano journals”, and the results of MEYER & PERSSON (1998) regarding the earlier period of nanotechnology.

4.2 Patterns of interdisciplinarity

The findings of Section 4.1, nanoscale research’s higher multidisciplinarity without considerably higher interdisciplinarity than classical disciplinary research, can be further discussed with reference to their corresponding molecular graphs (Figure 4).

JACS, as one would expect, is vastly dominated by its “mother discipline”, chemistry ($c_C = 89\%$). Chemists’ tendency to engage in interdisciplinarity, indicated by the chemistry-specific interdisciplinarity index ($si_C = 29.8\%$), is relatively low in *JACS* compared to chemists in nanoscale research ($si_C = 45.0\%$, Table 9). However, chemists in *JACS* entertain strong asymmetrical relation (see Section 3.5) to four much smaller, peripheral disciplines: biomedical science, materials science, physics, and chemical engineering. In fact, most authors from peripheral disciplines are involved in interdisciplinary research with chemists; their specific interdisciplinarity index ranges from 70% to 100%. They thus show typical features of auxiliary or consultant disciplines in a given research setting with topics defined by the main discipline.

Table 9. Interdisciplinarity Matrix and discipline-specific interdisciplinarity indices (si_i)

$c_{i,k}$ (in %)	P	C	B	M	ME	EE	CE	IC	(si_i)
P	15.9	4.9	0.9	2.8	0.7	5.0	1.3	0.4	47.2
C	4.9	14.2	1.8	3.5	0.1	1.4	1.0	0.3	45.0
B	0.9	1.8	2.4	0.7	0.3	0.1	1.0	0.1	61.5
M	2.8	3.5	0.7	7.7	0.1	2.0	1.3	0.4	30.7
ME	0.7	0.1	0.3	0.1	4.2	0.7	0.1	0.0	33.6
EE	5.0	1.4	0.1	2.0	0.7	12.3	1.3	0.0	43.5
CE	1.3	1.0	1.0	1.3	0.1	1.3	3.2	0.0	57.7
IC	0.4	0.3	0.1	0.4	0.0	0.0	0.0	0.1	82.8

However, interdisciplinarity in *JACS* is not restricted to unilateral, centripetal connections to chemistry. The setting also allows of small connections among the peripheral disciplines. In sum, the interdisciplinarity pattern of chemistry, as an example of classical disciplinary research, shows the following characteristics: the central and dominating discipline entertains strong asymmetrical relations to a couple of small, peripheral disciplines that are slightly connected to each other.

In contrast, the interdisciplinarity pattern of nanoscale research (Figure 4) shows four main disciplines of comparable size (physics, chemistry, electrical engineering, and materials science) related to each other by relatively weak symmetrical connections. In addition, three smaller, peripheral disciplines (chemical engineering, biomedical sciences, and mechanical engineering) are weakly connected to three, one, and none of the main disciplines, respectively. In nanoscale research there are more interdisciplinary connections than in *JACS* but they are generally weaker. With the exception of the chemistry-biomedical science relation, connections appear less selective but rather as everything-is-connected-to-everything, albeit on a low level. Furthermore, the discipline-specific interdisciplinarity indices do not vary as much and do not show the same pattern as in *JACS*; for three of the main disciplines it is around 45% and for two of the peripheral it is about 60%, while both a main discipline (materials science) and a peripheral discipline (mechanical engineering) are only little over 30%. Mechanical engineering's little and less selective tendency towards interdisciplinarity even puts it in isolation at the periphery.

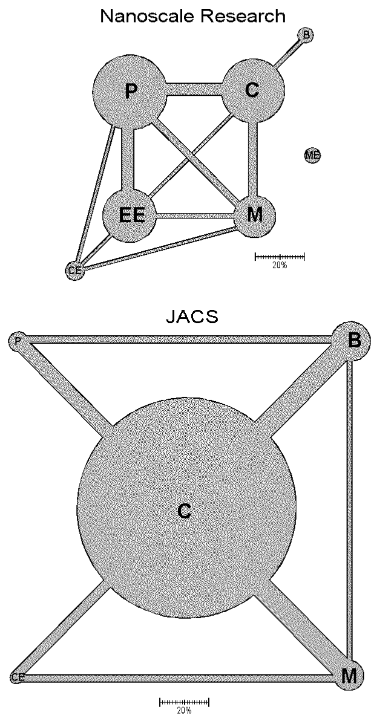

Figure 4. Molecular graphs of the interdisciplinary structure of nanoscale research and of the *Journal of the American Chemical Society* (*JACS*) at the same scale. Data correspond to the numerical representations of Tables 8 and 9; for disciplinary categories and abbreviations see Table 5

Nanoscale research's higher multidisciplinarity without considerably higher interdisciplinarity, but with more scattered and less selective interdisciplinary relations, suggests that it consists of an artificial composition of different research fields with little to no relation to each other. For further investigation, the eight "nano journals" are analyzed separately (see Table 10 and Figure 5). Indeed, except the *Journal of Nanoparticle Research*, all "nano journals" have a clear focus on a single discipline that dominates the interdisciplinary structure both regarding number and size of its interdisciplinary connections and its relative size. For three journals – *Nano Letters*, *Fullerenes*, and *JVCT-B*, their interdisciplinarity patterns is so close to the pattern of *JACS* that they are, indeed, indistinguishable from classical disciplinary research.

Table 10. The relative size of disciplines and multi- and interdisciplinarity indices by “nano journals”

Journal	c_P	c_C	c_B	c_M	c_{ME}	c_{EE}	c_{CE}	c_{IC}	$M^{.05}$	c^{max}	i^{max}	I^2	I^3
Nanotech	51.4	18.1	6.7	15.2	7.6	21.0	5.7	1.9	7	51.4	P	37.1	9.5
Nano Let	23.3	59.2	7.8	17.5	1.0	3.9	6.8	1.0	5	59.2	C	36.9	8.7
JVCT-B	25.0	7.7	2.9	16.3	4.8	46.2	8.7	0.0	5	46.2	EE	42.3	3.8
J Nanopart	25.5	9.8	17.6	19.6	5.9	9.8	25.5	0.0	7	25.5	P/CE	17.6	3.9
Fullerenes	18.9	78.4	5.4	18.9	0.0	5.4	2.7	0.0	5	78.4	C	27.0	2.7
Precision E	1.4	0.0	1.4	2.9	51.4	5.7	0.0	0.0	2	51.4	ME	20.0	0.0
Physica E	77.2	3.8	0.0	3.8	0.0	21.5	0.0	0.0	2	77.2	P	17.7	0.0
JNN	25.0	25.0	13.3	38.3	6.7	15.0	8.3	3.3	7	38.3	M	55.0	6.7

The journal *Nanotechnology* differs from that pattern only by its stronger centralization, since there are more peripheral disciplines connected to the central main discipline, physics, without allowing independent connections on the periphery. For two journals, *Physica E* and *Precision Engineering*, their multidisciplinarity and interdisciplinarity indices are so much lower than those of *JACS* that they fall much below the standards of classical disciplinary research. Instead, their pattern reveal that they are highly specialized journals in subfields of their corresponding “mother disciplines”, physics and mechanical engineering, respectively.

Only one journal, the *Journal of Nanoscience and Nanotechnology*, stands out because of its high level of interdisciplinarity ($I^2 = 55\%$) combined with a high degree of multidisciplinarity ($M^{.05} = 7$, $c^{max} = 38.3\%$). Although the structure is clearly dominated by materials science, both regarding its relative size and the number and size of its connections, other disciplines play a considerable and independent role as well. It is rather that kind of pattern that one would expect from a research field with extraordinarily high interdisciplinarity.

Finally, the exceptional *Journal of Nanoparticle Research* does not only lack a dominating central discipline and thereby shows the highest degree of multidisciplinarity ($M^{.05} = 7$, $c^{max} = 25.5\%$), it has also the lowest interdisciplinarity index ($I^2 = 17.6\%$). Like the overall pattern of nanoscale research, the combination of high multidisciplinarity with low interdisciplinarity goes along with many very weak interdisciplinary connection without any selectivity. A comparison of the two molecular graphs suggests that, similar to the overall field, albeit with different disciplinary emphasis, the journal might be a collection of papers from rather unrelated research fields, compiled by the editor. Since the journal editor, Michael Rocco, is also the director of the National Nanotechnology Initiative and as such the leading political architect of the nanoscale research landscape in the US, the assumption is not implausible and would suggests that the editorial efforts to increase multidisciplinarity go at the expense of interdisciplinarity.

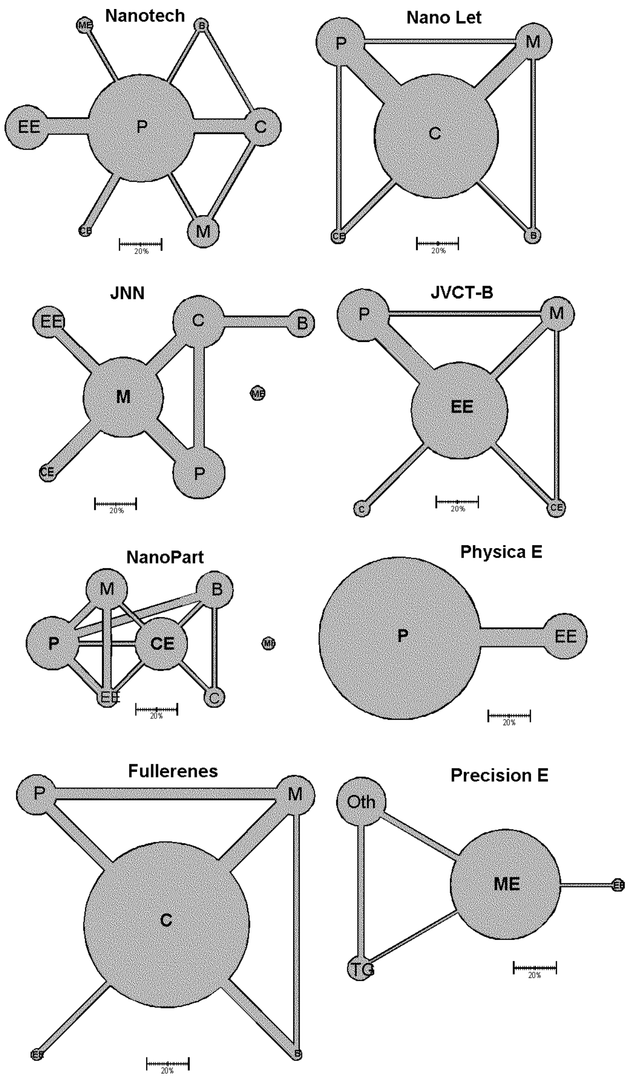

Figure 5. Molecular Graphs of the interdisciplinary structure of the eight "nano journals" described in Tables 3 and 4 (data are partly represented in Table 10)

We may now draw our second conclusion, which at the same time explains conclusion number one: Nanoscale research as represented by the eight "nano journals" is anything else than a homogenous interdisciplinary research field. Instead, under the umbrella of "nano", classical disciplinary patterns have continued or reproduced themselves without much interaction between them. This has led to two "nano-physics journals" (*Nanotech* and *Physica E*), two "nano-chemistry journals" (*NanoLet* and *Fullerenes*), one "nano-materials science journal" (*JNN*), one "nano-electrical engineering journal" (*JVCT-B*), one "nano-mechanical engineering journal" (*Precision E*), and a strongly edited journal that informs a broad readership from many different disciplines (*J Nanopart*).

Since four of the "nano journals" are published by disciplinary societies or institutions (see Table 3), their result might have been predictable. Yet, the others show disciplinary patterns as well. The fact that similar patterns persist, independent from publishers or particular disciplines and of similar appearance in the natural sciences and in engineering, suggests that, beyond any disciplinary peculiarities, general social forces control disciplinary integrity and the degree of interdisciplinary collaboration. It appears questionable if science policy has remarkable impact on that and if high interdisciplinarity automatically arises out of high multidisciplinarity, which one might be able to induce, rather than the opposite. Instead, the notorious vagueness of definitions of "nanoscale research" allows each discipline to maintain topical domination in their respective journals. Quite likely, we will see a climate of increased competition among the disciplines with new journals being launched that, as the Institute of Electrical and Electronics Engineers boldly claims for their yet to be published *Transactions on Nanotechnology*, want to "take the leading international role in disseminating knowledge in nanotechnology".[*]

On the other hand, the degree of interdisciplinarity in classical disciplinary research is, despite the overwhelming domination by the main discipline, remarkably high, as the case of *JACS* illustrates. And some of the "nano-journals", which retain the pattern of classical disciplinary research, show even higher degrees of interdisciplinarity. Thus, the current model of a bunch of disciplinary-focused nanoscale research fields might well lead to increased interdisciplinarity – and would do so by preserving the autonomy of the disciplines. It is an open question, of course, if this pattern of increased interdisciplinarity, at the expense of the more visible multidisciplinarity, is desirable by

[*] Quoted from the journal's website, http://www.ieee.org/products/nanotechnology/ (8 June 2003).

science policy makers. Anyway, distinguishing patterns of interdisciplinarity may help move the debate on interdisciplinarity to a more sophisticated level such that we may ask which kind of interdisciplinarity is desirable and which not.

4.3 Interinstitutional and intercontinental collaboration

Interdisciplinary collaboration is but one form of research collaboration to be studied by co-author analysis. This section discusses the collaboration in nanoscale research between different institutions and between different geographical regions. The analysis of data and the visualization of results follow the same formal procedure as with interdisciplinary collaboration (see Section 3). In addition, since each paper is characterized by disciplinary, institutional, and geographical categories, one can easily analyze correlations between the three categories. To restrict such cross-categorial correlations to a reasonable limit, I will discuss only three questions that are related to issues of multi- and interdisciplinarity: How does the collaboration of university researchers with industry vary by discipline? Are there geographical differences in the tendency towards interdisciplinary research? Does the notion of nanoscale research, in terms of its multidisciplinary composition, differ by geographical region?

4.3.1 Interinstitutional collaboration and patterns of inter- and multidisciplinarity. Most of the results regarding interinstitutional collaboration in nanoscale research are hardly surprising and follow common patterns (see Table 11 and Figure 6). Nanoscale research shows the typical profile of academic research journals in that the vast majority of papers are co-authored by scholars from university (82.1%) to be followed at a much lower level by co-authorship from governmental research institutes (24.7%) and industry (17.8%). Compared to our reference journal, *JACS*, industrial authorship is almost doubled, at the expense of university authorship, but the difference is only due to the two engineering journals, *JVCT-B* and *Precision Engineering*, in which authors from industry clearly outweigh authors from research institutes.

Both the collaboration between university and research institutes and between university and industry show patterns of relative strong asymmetric connections, reminding of auxiliary disciplines in interdisciplinarity patterns. Universities clearly dominate the field, as researcher from the smaller institutions, industry and research institutes, show strong tendencies towards collaboration with scholars from university (Table 12). Despite the increasing governmental pressure towards economically useful research and even despite their partial privatization in many countries, governmental research institutes appear to have serious difficulties to engage with industry, since the direct collaboration between the two of them is insignificant. Instead, collaboration between research institutions and industry is largely mediated by universities, such that threesome collaboration is the dominating form here.

Table 11. Interinstitutional collaboration

	c_{Uni}	c_{Gov}	c_{Ind}	$c_{Uni,Gov}$	$c_{Uni,Ind}$	$c_{Gov,Ind}$	$c_{Uni,Gov,Ind}$	I_I^2
Nanotech	85.7	23.8	10.5	12.4	4.8	1.0	1.0	19.0
Nano Let	87.4	28.2	9.7	14.6	3.9	1.0	2.9	22.3
JVCT-B	74.0	24.0	35.6	9.6	10.6	1.9	5.8	27.9
J Nanopart	78.4	21.6	11.8	5.9	5.9	0.0	0.0	11.8
Fullerenes	86.5	40.5	2.7	27.0	2.7	0.0	0.0	29.7
Precision E	84.3	12.9	21.4	5.7	8.6	1.4	1.4	17.1
Physica E	91.1	22.8	2.5	13.9	2.5	0.0	0.0	16.5
JNN	81.7	23.3	10.0	6.7	5.0	0.0	1.7	13.3
Nano Research	82.1	24.7	17.8	11.4	6.4	1.1	2.9	21.7
JACS	91.0	26.0	9.0	18.0	6.0	0.0	1.0	25.0

The definitions of the indices follow the general definitions provided in Section 3.4. For instance, c_{Uni} is the proportion of papers co-authored by at least one university researcher, and $c_{Uni,Gov}$ is the proportion of paper co-authored by at least one university researcher and at least one author from governmental research institutes. I_I^2 is (analogous to I^2) the interinstitutional index defined by the relative number of papers co-authored by authors from at least two categorially different institutions.

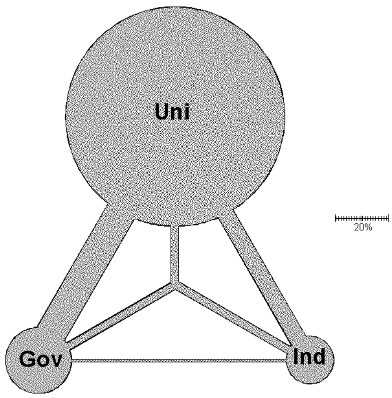

Figure 6. Molecular graph of the interinstitutional collaboration between university (Uni), research institutes (Gov), and industry (Ind) in nanoscale research (for details of the institutional categories see Table 6)

Table 12. Institution-specific interinstitutional indices[a]

	si_{Uni}	si_{Gov}	si_{Ind}
Nano Research	25.2	62.1	57.9
JACS	27.5	73.1	77.8

[a] Defined analogous to the discipline-specific interdisciplinarity indices in Section 3.4; describes the relative tendency of authors of a certain institution to collaborate with researchers from other institutions.

Since this study does not assign disciplinary labels to authors from industry for reasons discussed in Section 3.3, we can study the collaboration between industry and the individual disciplines involved in nanoscale research (Table 13 and Figure 7). Unlike what complementary "nano-title-paper" and "nano-title-patent" citation studies suggest about the early nano-science/nano-technology relation (cf. MEYER, 2000; and again MEYER, 2001), industry appears like a medium sized discipline connected to all the disciplines with small to medium sized collaboration coefficients. For electrical engineering and mechanical engineering, industrial collaboration is even stronger than their collaboration with any other discipline. Overall, industrial collaboration with electrical engineering and physics is dominating and leads to results mostly published in *JVCT-B*, which suggests that the electronics industry is the main partner in current nanoscale research.

Table 13. Discipline-specific collaboration with industry

	$c_{P,Ind}$	$c_{C,Ind}$	$c_{B,Ind}$	$c_{M,Ind}$	$c_{ME,Ind}$	$c_{EE,Ind}$	$c_{CE,Ind}$
Nanotech	3.8	1.0	1.0	1.0	0.0	2.9	1.9
Nano Let	2.9	4.9	1.0	3.9	0.0	1.0	1.0
JVCT-B	8.7	1.0	1.0	3.8	1.9	13.5	1.9
J Nanopart	0.0	0.0	0.0	0.0	2.0	2.0	3.9
Fullerenes	0.0	2.7	0.0	2.7	0.0	0.0	0.0
Precision E	1.4	0.0	0.0	0.0	8.6	0.0	0.0
Physica E	1.3	0.0	0.0	1.3	0.0	2.5	0.0
JNN	1.7	1.7	1.7	3.3	0.0	1.7	1.7
Nano Research	4.3	1.9	0.8	2.8	1.1	5.2	1.5
JACS	-	8.0	3.0	2.0	-	-	-

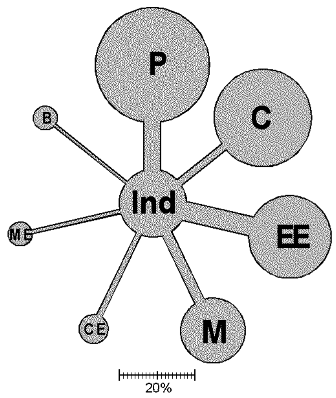

Figure 7. Molecular graph of the collaboration between the disciplines and industry (interdisciplinary relations are omitted for graphical reasons, see Figure 4)

Table 14. Discipline-specific industrial collaboration indices[a]

	$si_{P,Ind}$	$si_{C,Ind}$	$si_{B,Ind}$	$si_{M,Ind}$	$si_{ME,Ind}$	$si_{EE,Ind}$	$si_{CE,Ind}$
Nano Research	14.1	7.5	12.9	16.2	18.1	23.9	19.7
JACS	-	9.0	18.8	15.4	-	-	-

[a] Defined analogous to the discipline-specific interdisciplinarity indices in Section 3.4; describes the relative tendency of authors of a certain discipline to collaborate with researchers from industry.

The discipline-specific industrial collaboration index ($si_{i,Ind}$ in Table 14) describes each discipline's relative tendency toward industrial collaboration. Almost a quarter (23.9%) of all papers co-authored by electrical engineers include industrial collaboration. The two other engineering disciplines, chemical engineering (19.7%) and mechanical engineering (18.1%), follow shortly (although the error in smaller disciplines is bigger because of the smaller absolute numbers of cases). Next comes materials science & engineering with 16.2% to be followed by physics (14.1%), biomedical science & engineering (12.9%), and chemistry (7.5%).

While the positions of materials science & engineering and of biomedical science & engineering between the natural sciences and the engineering disciplines are probably not surprising, the relatively big difference between physics and chemistry certainly is. A comparison with data from *JACS* (Table 14) proves that chemistry's tendency toward industrial collaboration in nanoscale research corresponds to its medium value cross all kinds of chemical research. On the other hand, physics' much higher tendency towards industrial collaboration in nanoscale research becomes less surprising if we compare the interdisciplinary ties to engineering (Table 9). In nanoscale research, physics entertains stronger relations than chemistry not only to electrical engineering and mechanical engineering, but also to chemical engineering. This suggests that the kind of physics involved in nanoscale research is dominated by so-called applied physics.

4.3.2 Intercontinental collaboration, multidisciplinary patterns, and the notion of nanoscale research. Given the competition in governmental funding of nanoscale research (Section 1), it might be interesting to compare the research outcome in different countries. In terms of authorship of research papers, the output roughly corresponds to the input of money (see Table 15 and Figure 8). North American authors make up the strongest group (41.6%), European and Asian authors are somewhat lower on equal level (31.0% and 30.9%), and the rest of the world adds up to as little as 6.1%. However, since one would expect a similar picture in many other research fields, the correspondence does not support any simple conclusion. In contrast, there is considerable nanoscale research output from countries like China and Korea, although their research budgets in USD do not appear on "hit lists" of nanoscale research funding countries. This section therefore focuses on collaboration, instead of competition, and asks if there are geographical or cultural differences regarding both interdisciplinary collaboration and the multidisciplinarity of nanoscale research.

Compared to both the interdisciplinarity index (I^2=36.5%) and the interinstitutional index (I_I^2=21.7%), the geographic collaboration index (I_G^2=9.7%) appears quite low. Yet, given the actual efforts required for research collaboration between different continents, it is remarkable that a tenth of the papers have authors from at least two different continents. Indeed, science is a social subsystem with a very high degree of international exchange. The different indices for the "nano journals" as well as the high index for *JACS* – after all, a journal of a national society – reveal that intercontinental collaboration is even much higher in the natural sciences than in the engineering disciplines (Table 15).

Table 15. Collaboration between geographic regions

	c_{NA}	c_{EU}	c_{AS}	c_{Oth}	$c_{NA,EU}$	$c_{NA,AS}$	$c_{NA,Oth}$	$c_{EU,AS}$	$c_{EU,Oth}$	$c_{AS,Oth}$	I_G^2
Nanotech	21.0	41.0	43.8	4.8	3.8	1.0	0.0	3.8	1.0	1.0	10.5
Nano Let	64.1	31.1	9.7	6.8	3.9	2.9	2.9	1.0	2.9	0.0	12.6
JVCT-B	38.5	23.1	42.3	2.9	1.9	3.8	0.0	0.0	1.0	0.0	6.7
J Nanopart	43.1	33.3	19.6	13.7	5.9	0.0	3.9	0.0	0.0	0.0	9.8
Fullerenes	13.5	67.6	27.0	5.4	8.1	5.4	0.0	2.7	0.0	0.0	10.8
Precision E	30.0	24.3	52.9	1.4	0.0	4.3	1.4	2.9	0.0	0.0	8.6
Physica E	20.3	49.4	31.6	13.9	5.1	2.5	0.0	2.5	5.1	0.0	15.2
JNN	48.3	18.3	30.0	10.0	1.7	3.3	1.7	0.0	0.0	0.0	6.7
Nano Research	41.6	31.0	30.9	6.1	3.2	2.9	1.2	1.2	1.5	0.1	9.7
JACS	55.0	42.0	13.0	7.0	6.0	2.0	3.0	6.0	2.0	1.0	14.0

The definitions of the indices follow the general definitions provided in Section 3.4. For instance, c_{NA} is the proportion of papers co-authored by at least one researcher from North America, and $c_{NA,EU}$ is the proportion of papers co-authored by at least one researcher each from North America and Europe. I_G^2 is (analogous to I^2) the geographic collaboration index defined by the relative number of papers co-authored by authors from at least two categorially different geographical regions.

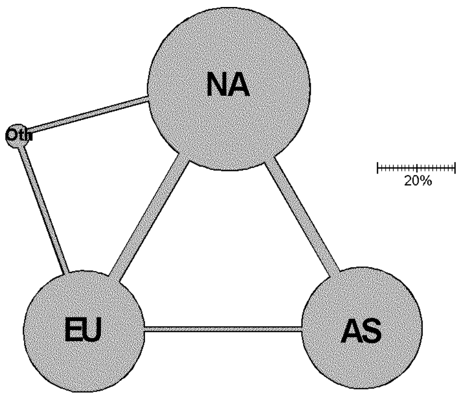

Figure 8. Molecular graph of the collaboration between North America (NA), Europe (EU), Asia (AS), and Others in nanoscale research (for details of the categories see Table 7.)

Figure 8 illustrates the different degrees of research collaboration between different geographic regions or continents. Researchers from North America collaborate at similar rates with both Europeans and Asians, between which collaboration is much lower. In fact, Europeans work together less with Asians than with the residual group of various others countries. The fact that Asians show no significant relation to this diverse group of Others reveals their relatively selective collaboration focus on Europe and North America, as MEYER & PERSSON (1998) have already found for the early period of nanoscale research.

The relative tendency towards intercontinental research collaboration, as measured by the region-specific geographic collaboration indices, differs from region to region (see Table 16). Researchers from other countries show by far the highest specific collaboration index (si_{Oth}=42.7%). Once again there is the same pattern we have found for auxiliary disciplines and small institutions: minority groups show an extraordinary high tendency to collaborate with the dominating group(s) in order to become involved at all. (The same phenomenon can be observed in *JACS* where also Asian authors are a minority group who highly collaborate with the major groups, see Table 16.) Authors from Europe and North America seek intercontinental research collaboration at a similar rate, the former being only slightly higher, while the inclination of Asian authors is significantly lower. Yet, the difference is only because, in nanoscale research, Asian researchers are much more engaged in engineering (see below) where international collaboration is significantly lower than in the natural sciences.

This leads to the final question. We have seen that the overall field of nanoscale research is composed of an impressively multidisciplinary bunch of disciplines only loosely related to each other (Figure 4), and that there are three groups from different geographical regions dominating the overall field. The question then is if North Americans, Europeans, and Asians set different disciplinary priorities in nanoscale research and thus prefer different multidisciplinarity patterns. If so, they might also have quite different notions of what nanoscale research is all about, given the vagueness of definitions.

Table 16. Region-specific geographic collaboration indices[a]

	si_{NA}	si_{EU}	si_{AS}	si_{Oth}
Nano Research	16.8	18.0	13.3	42.7
JACS	16.4	26.2	53.8	57.1

[a] Defined analogous to the discipline-specific interdisciplinarity indices in Section 3.4; describes the relative tendency of authors of a certain region to collaborate with researchers from other regions.

Table 17. Interdisciplinarity indices by geographic region

	I^2_{NA}	I^2_{EU}	I^2_{AS}
Nano Research	42.8	37.0	34.7
JACS	29.1	38.1	61.5

Figure 9 presents, each for North America, Europe, and Asia, the relative proportions of authors by disciplines. Obviously each geographical region has its particular nanoscale research profile. In Europe, this is largely dominated by the pair of physics and electrical engineering, which amounts to almost 70%.* While chemistry, biomedical science, and materials science are relatively small, the European profile also stands out because of its virtual lack of chemical engineering and mechanical engineering. In North America, chemistry is the dominating "nano science" with additional relative strengths in biomedical science, chemical engineering, and mechanical engineering, whereas physics and, even more so, electrical engineering are relatively small.

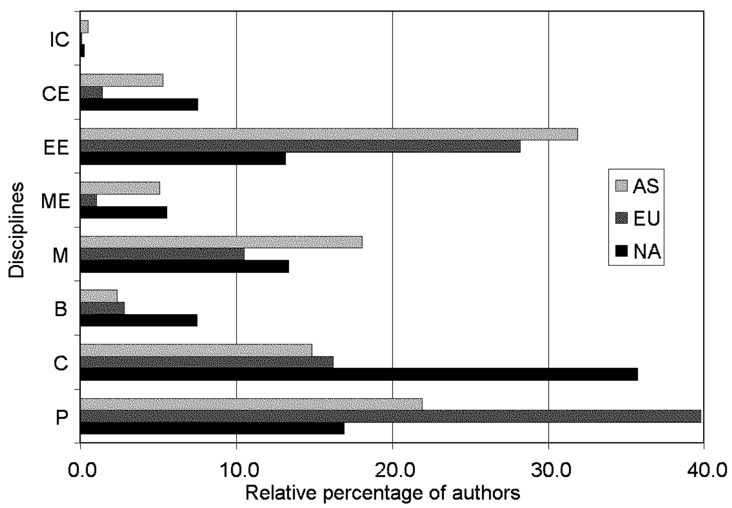

Figure 9. Relative percentages of authors by disciplines each for North America (NA), Europe (EU), and Asia (AS) (for disciplinary categories, see Table 5). Authors from other geographical regions and authors of papers with intercontinental collaboration are excluded

* This focus corresponds to the results of the Delphi survey reported in MALSCH (1999).

Asia has the most balanced pattern, with relative strengths in electrical engineering and materials science, and relative weaknesses in biomedical sciences and chemistry. However, Asian nanoscale research puts much more emphasis on engineering than on science, compared to both North America and Europe.

Obviously there is only a single discipline to which all three groups attach about the same degree of importance in nanoscale research, which is materials science and engineering. Within some tolerance, there is agreement each between two groups on the relative importance (or unimportance) of the other six disciplines. North Americans and Asians agree on the relative importance (or unimportance) of physics, mechanical engineering, and chemical engineering, whereas Europeans and Asians agree on the relative importance (or unimportance) of chemistry, biomedical science, and electrical engineering. Thus, the pattern of agreement and disagreement does not allow drawing any conclusion about majority opinions. The most striking result, however, is that there is no agreement between North Americans and Europeans on the relative importance of any discipline to nanoscale research, other than about materials science. That is surprising because these two groups collaborate most and because their collaboration is mainly in chemistry and physics (see the data for *Fullerenes* and *Physica E* in Table 15).

In sum, despite the collaboration on individual research projects, there is little agreement on the multidisciplinary composition of nanoscale research among the main geographic or cultural groups.[*] This suggests that there is not one but at least three culturally different notions of nanoscale research. However, the difference in this notion between the groups seems to have no negative impact on their research collaboration, which suggest that the notion of nanoscale research might be, like a label, rather irrelevant to their research. In other words, rather than an integrating idea of nanoscale research, it is the individual disciplinary ties on which intercontinental research collaboration seems to be built.

5. Conclusion

Since a couple of years, many countries have, like in an international competition, spent tremendous amounts of governmental funds for nanoscale research at breathtaking speed. With definitions of nanoscale research being notoriously vague, this has created new space of research opportunities that attracts many different disciplines on a large

[*] According to earlier reports, there was not even much agreement among European experts, see BUDWORTH (1996), MALSCH (1997b).

scale and with unprecedented velocity. In fact, if measured by the number of "nano-title-papers", the current dynamics would, only in a few years, lead to the strange situation that almost the whole of science and engineering might be called nanoscale research. Even if the present dynamics is but hype and "nano" but a buzz word that might soon disappear again, the new space of research is also an opportunity for many disciplines to engage in new forms of interdisciplinarity. Because interdisciplinarity in nanoscale research is one of the outspoken desiderata of science policy makers, and because, at least in the US, a reorganization of the entire research landscape around nanotechnology is being debated (ROCO & BAINBRIDGE, 2002), this might be more than just a welcome side-effect.

The present study has investigated multi- and interdisciplinarity as well as interinstitutional and intercontinental research collaboration in current nanoscale research by applying co-author analysis to the eight existing "nano journals" and to one classical disciplinary journal for reference and comparison reason. The entire field of nanoscale research shows only an average degree of interdisciplinarity, comparable to classical disciplinary research, but a high degree of multidisciplinarity. Analyzed separately, however, these "nano journals" turn out to be classical disciplinary journals of physics, chemistry, electrical engineering, mechanical engineering, and materials science, respectively. In sum, current nanoscale research is neither particularly interdisciplinary nor particularly multidisciplinary, because there is not one field of nanoscale research but several different fields of "nano-physics", "nano-chemistry", "nano-electrical engineering", etc., which are quite unrelated to each other. In other words, nanoscale research is multidisciplinary only in the same trivial sense that the whole of science and engineering is multidisciplinary. Also, despite the simultaneous push of nanoscale research in many countries and institutions, nanoscale research does not differ from the received practice in science and engineering regarding intercontinental and interinstitutional research collaboration.

Furthermore, while we have relatively clear and culturally universal ideas of what belongs to the whole of science and engineering and what not, as reflected for instance in the departmental structure of universities, there is no such idea regarding nanoscale research. Instead, opinions about what belongs to nanoscale research and what not considerably differ from country to country, which suggest that there are culturally different, albeit equally vague if not plastic, notions of nanoscale research. Both the disciplinary and the cultural diversity of the notion of nanoscale research do not provide any conceptual integration of the different disciplines and thus do not foster but hinder research collaboration.

Notwithstanding large political efforts towards its generation, interdisciplinarity of research is still a poorly understood, complex phenomenon and should not be confused with multidisciplinarity or with the interdisciplinarity of information, which is simply a matter of classification. It has been one goal of the present study to develop a more sophisticated conceptual framework for describing, visualizing, and analyzing both multi- and interdisciplinarity of research. This has allowed distinguishing between different patterns of interdisciplinarity and to conclude that the "nano journals" reveal similar patterns of interdisciplinarity as classical disciplinary research. Classical disciplinary research combines a relatively high degree of interdisciplinarity with a low degree of multidisciplinarity, due to the domination of the "mother discipline" to which many small "auxiliary disciplines" are strongly connected.

Once different patterns of interdisciplinarity are distinguished, we may ask which kind of interdisciplinarity is desirable and which not and for what reasons. And only after the dynamics of interdisciplinarity is much better understood, one can start making reasonable efforts to direct it. Although the present study is not about dynamics, it includes some evidence to support two hypotheses. First, increasing multidisciplinarity does not automatically lead to higher but rather to lower degrees of interdisciplinarity, which is easily overlooked if both concepts are not clearly distinguished from each other. Secondly, a strong social distinction between major and minor disciplines can induce relatively high degrees of research collaboration, because minority groups, in order to become involved at all, show extraordinary tendencies to collaborate with majority groups. This has been a recurrent pattern in all three forms of research collaboration – interdisciplinary, interinstitutional, and intercontinental. Both hypotheses together suggest that the ideal picture of a variety of disciplines at equal rank and with strong connections between each other might be sociologically too naive. They further suggest that classical disciplinary research includes the potential of higher degrees of interdisciplinarity, though at low levels of multidisciplinarity. However, once again, if that pattern of interdisciplinarity is desirable or not, is an open question.

It goes without saying that the two main patterns of interdisciplinarity – many disciplines at equal rank and with strong symmetrical connections between each other versus one dominating discipline with strong asymmetrical connections to many auxiliary disciplines – flourish on quite different social grounds. The second pattern not only draws on the historically grown demarcations lines and neighboring relations between disciplines, but also on the established social infrastructure of its "mother discipline", including research institutes, career networks, curricula, professional societies, journals, and so on, all of which are rather obstacles to establishing the first pattern. Cultivating the first pattern would, in contrast, require the establishment of a new, independent social infrastructure for the corresponding interdisciplinary research field.

For current nanoscale research, tremendous financial efforts have been made in that direction, which is partly reflected in the results of the present study. Indeed, 167 authors of the analyzed papers mention, in addition to their disciplinary affiliation, their affiliation to a "nano institution", such as a nano-center or nano-laboratory. Regardless of their different disciplinary affiliation, these "nano-fellows" strongly collaborate with each other, such that on average 3.1 "nano-fellows" co-author one paper. This suggests that establishing a new social infrastructure, of which nano-centers and the like are only one element, are effective means to foster interdisciplinarity of the first pattern.

However, it is very unlikely that the first pattern of interdisciplinarity can be more than a temporary occurrence. On the one hand, there are also strong cognitive barriers to interdisciplinary collaboration in nanoscale research which cannot simply be overcome by referring to the ubiquitous nanometer scale of research objects (SCHUMMER, forthcoming). On the other hand, if not absorbed into established disciplines, interdisciplinary research frequently moves into the formation of a new (hybrid) discipline, as the recent and, for nanoscale research, most relevant case of materials science and engineering illustrates (BENSAUDE-VINCENT, 2001). Despite, or probably because of, its interdisciplinary origin and "ongoing process of hybridization" (ibid., p. 246), materials scientists and engineers in nanoscale research show very little inclination towards interdisciplinary research collaboration (see Table 9). Thus, interdisciplinarity can via new discipline formation turn into relatively closed disciplinary structures. That is only one of the many strange features of disciplinary dynamics, which is still too little understood to encourage current political ambitions to control and direct the development (ROCO & BAINBRIDGE, 2002).

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