Where does nanotechnology belong in the map of science?

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By analysing publication and citation data, it is possible to explore the relationships between nanoscience and nanotechnology and the rest of science and technology.

It is commonplace to read that nanoscience and nanotechnology are highly multidisciplinary, and that the convergence of nanotechnology, biotechnology, information technology and cognitive sciences (NBIC) will lead to big changes in many aspects of our lives and modern society[1,2]. Understanding the multidisciplinary nature of nanoscience and nanotechnology, and their relationships with other areas of research, is therefore important for science policy, funding, research management and effective knowledge transfer.

A number of researchers have used bibliometric techniques to explore this multidisciplinary nature. For example, an analysis of the Science Citation Index (SCI; a database containing information on about 6,650 journals in most fields of science[3]) that used phrases and citations to search for topical structures in the nanoliterature showed that nanotechnology (as defined in refs 4 and 5) encompassed a range of diverse applications[4,5]. A study of a large government-funded nanotechnology project in Japan that examined publication patterns, and also looked at the extent of knowledge transfer between technology and science, concluded that the project had been notably interdisciplinary[6]. In May 2008, Grodal and Thoma presented another study at the National Bureau of Economic Research conference on 'Emerging Industries: Nanotechnology and NanoIndicators' that tracked the migration of detailed concepts through large datasets of publications (using SCI), patents (from the US Patent and Trade Office) and press releases (Lexis-Nexis). They found that the cross-pollination of knowledge between nanotechnology and biotechnology had instigated the rapid emergence of a new field called nanobiotechnology (S. Grodal & G. Thoma, personal communication). However, a different study of patent data concluded that much of the apparent convergence of nanotechnology and biotechnology to give nanobiotechnology was due to the use of common instrumentation, rather than true interdisciplinarity[7]. Furthermore, a project that used SCI subject categories to examine 600 nanotechnology papers published in 2002 and 2003 concluded that "under the umbrella of 'nano', classical disciplinary patterns have continued or reproduced themselves without much interaction between them"[8].

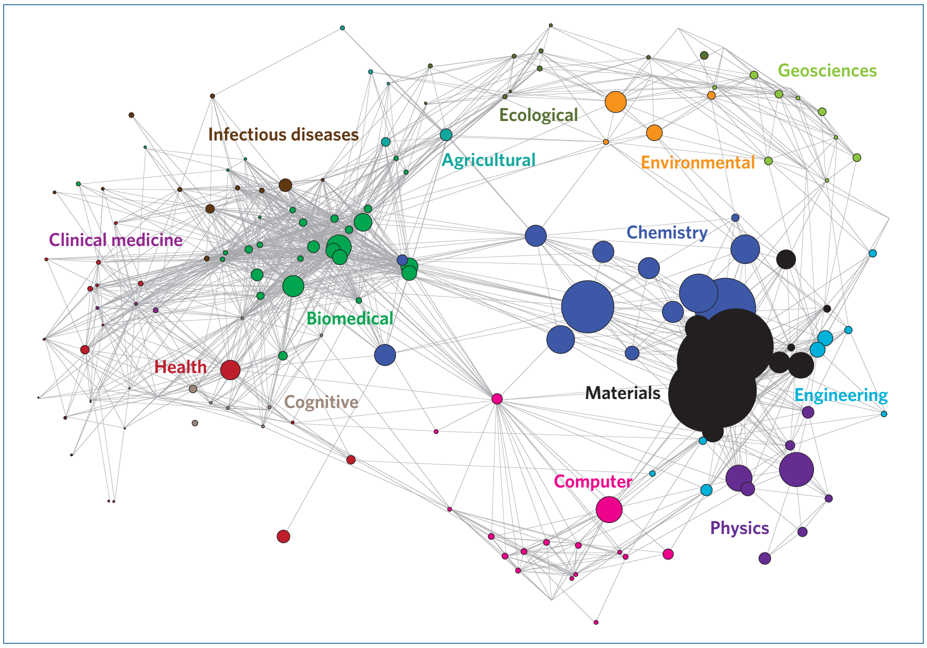

Figure 1 | The position of nanoscience and nanotechnology over a base map of science. Each node in this map[15] is one of the 175 subject categories in the SCI. The size of each node is proportional to the number of nanopapers published in journals in each subject category during the period January–July 2008. Location on the axes in this Kamada–Kawai algorithm representation has no inherent meaning: the connecting arcs and proximity reflect similarity based on cross-citation patterns, reinforced by colouring to reflect the clustering of subject categories into macrodisciplines (see Methods). See Table 1 for full macrodiscipline names.

Here we explore the cross-disciplinary nature of research in nanoscience and nanotechnology with a combination of metrics and maps. Previously we had developed a Boolean search strategy to retrieve the abstracts of nanoscience and nanotechnology papers from the SCI (see Methods and ref. 9), profiled this nanoliterature in terms of its interactions with the other fields of research it engaged, studied its evolution over time, and explored modes of interchange of research knowledge in the nanoliterature[10]. In this paper we use our Boolean approach to extract the abstracts of nanotechnology papers published in the period January–July 2008 (a total of 30,762 papers, hereafter called nanopapers or the nanoliterature), and then ask two questions: how broadly does this nanoliterature engage with the rest of the literature; and to what extent does the nanoliterature integrate knowledge from multiple disciplines?

To address the first question, we use the 175 subject categories in the SCI as a proxy for academic disciplines. These subject categories are widely used to define research fields in bibliometric studies, with organizations such as the National Academies and the Keck Foundation in the US using them to gauge cross-disciplinarity[11] and promote interdisciplinarity in research[12]. Interdisciplinary research is quantified in terms of the degree of integration of theories and/or techniques and/or data from two or more areas of research. The SCI subject categories suit this purpose well. Although classifications based on SCI subject categories can differ from those based on other approaches ~50% of the time (refs 13, 14 and K. W. Boyack, personal communication), it has been shown that these inaccuracies tend to cancel out for large datasets, and the overall 'map' structures produced by the different approaches are very similar[14].

Here we use a map of science[15] based on an analysis of more than 6,000 journals in the SCI database, and an overlay technique[16] to analyse multidisciplinarity of the nanoliterature (Fig. 1). We find that nanopapers have been published in 151 of the 175 subject categories in the SCI in the period January–July 2008, with 52 subject categories containing 100 or more of these papers. Elsewhere we have studied the evolution of these maps with time since 1991 (ref. 17).

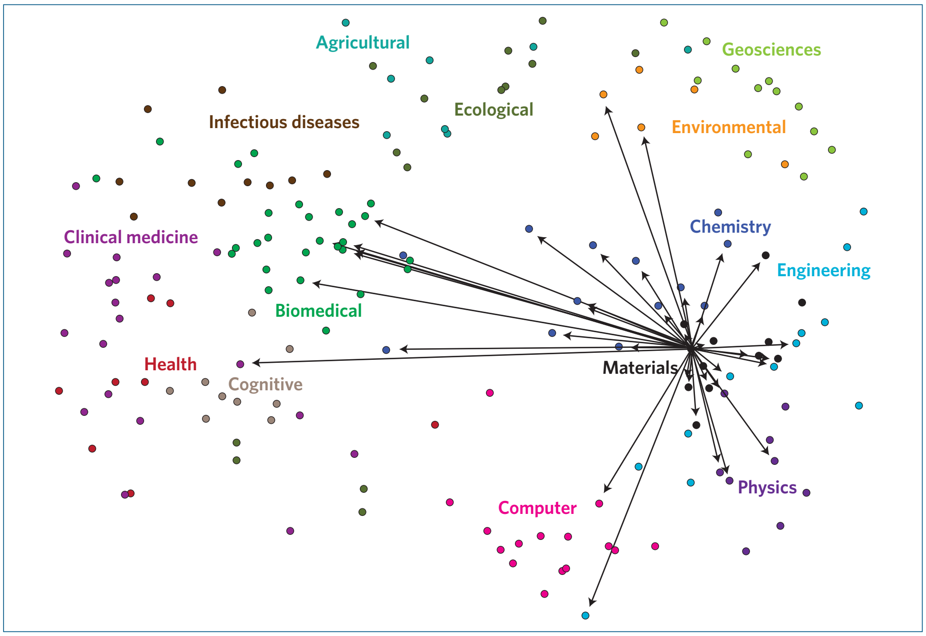

Figure 2 | Fields of science that are cited by nanotechnology papers. The arrows show the 40 subject categories most cited by papers published in the nanoscience and nanotechnology subject category during the period January–July 2008 (highlighted on the map of science shown in Fig. 1). It can be seen that papers from many different fields of science have influenced research on nanoscience and nanotechnology. See Table 1 for full macrodiscipline names.

To explore the question of knowledge integration, we then studied the papers cited by the nanopapers in our sample: this yielded just over 1,000,000 cited references (mean = 33.5, median = 28 per paper). Using text mining to extract sources from the cited references, and thesauri to match each reference's journal to subject categories, we found that 45 subject categories were cited by 5% or more of the nanopapers published in the period January–July 2008, and 98 subject categories were cited by at least 1% of these papers.

Six subject categories dominate both the original nanopapers and the cited references: 'materials science, multidisciplinary' contained the most nanopapers, followed by 'physics, applied', 'chemistry, physical', 'physics, condensed matter', 'nanoscience and nanotechnology', and 'chemistry, multidisciplinary'. Each of these subject categories contained 10% or more of the original papers, and was cited by 39% or more of them.

We can illustrate the multidisciplinary nature of nanotechnology by focusing on the 3,863 papers published in journals listed under 'nanoscience and nanotechnology' (a SCI subject category that was introduced in 2005). We find that 86% of these cite papers published in journals listed under 'materials science, multidisciplinary', with a further 80 subject categories having 40 or more cited papers each, and a total of 187 (including 32 from the social sciences and humanities) being cited at least once. This cross-disciplinary citation pattern is not exclusive to the nanoscience and nanotechnology subject category: for instance, the 808 nanopapers in the electrical engineering subject category cited papers in journals from 138 different subject categories, and the 435 nanopapers in the organic chemistry subject category cited papers in journals from 140 different subject categories. Research in nanoscience and nanotechnology is clearly not taking place in separate 'silos' (Fig. 2).

The 14 labels in Figs 1 and 2 are actually 'macrodisciplines', each of which contains a number of subject categories (see Methods). Table 1 ranks the 15 macrodisciplines that contained the most nanopapers, and also shows the percentage of nanopapers that cited references to the various macrodisciplines. Although the materials science and chemistry macrodisciplines dominate the first of these measures, the second confirms the influence of a wide variety of macrodisciplines on research in nanoscience and nanotechnology. Supplementary Table S1 explores the extent to which the nanopapers in a given macrodiscipline include references to papers published in other macrodisciplines.

In support of the National Academies Keck Futures Initiative to promote interdisciplinary research[12], we have developed a metric called the 'integration score' (see Methods) to gauge how interdisciplinary a particular paper or sets of papers is[18,19]. The integration score can range from zero (stand-alone discipline that does not cite work from other disciplines) to one (highly integrated discipline that heavily cites work from diverse disciplines). We have calculated the integration scores for the nanopapers in three subject categories and found them to be similar: nanoscience and nanotechnology, 0.65; electrical engineering, 0.60; and organic chemistry, 0.64.

These values are comparable to those for all papers (that is, not just nanopapers) in representative subject categories (for example, 0.60 for 'physics, atomic, molecular and chemical' and 0.66 for 'medicine, research and experimental'), but the figure for nanopapers in the electrical engineering subject category is considerably higher than that for all papers in this category (0.53).

These results affirm the multidisciplinary nature of research into nanoscience and nanotechnology, although the integration scores make it clear that much non-nano research is also comparably interdisciplinary. It is also clear that much nanoresearch is concentrated in the macrodisciplines of materials science and chemistry, and that researchers in the field tend to cite work in neighbouring fields more than work in more distant fields.

Table 1 | Macrodisciplines and nanotechnology.

Macrodiscipline	% of nanopapers in this macrodiscipline	% of nanopapers citing papers in this macrodiscipline
Materials science	50	85
Chemistry	44	83
Physics	11	57
Biomedical sciences	9	66
Engineering sciences	7	51
Computer science	3	21
Clinical medicine	3	15
Environmental science & technology	2	11
Agricultural sciences	1	9
Infectious diseases	1	7
Geosciences	1	6
Ecological sciences	<1	3
Cognitive sciences	<1	4
Health	<1	3
Business & management	<1	3

Percentage of nanopapers from the period January–July 2008 that were published in journals in various macrodisciplines, and percentage of nanopapers from this period that cite papers from these macrodisciplines. Percentages do not add up to 100% because some journals appear in more than one macrodiscipline. At present we use 18 macrodisciplines, of which 14 fit the sciences and are mapped in Figs 1 and 2. The four social science macrodisciplines have relatively few nanopublications or citations; business and management is the most prominent of these four.

Methods

Our search strategy (detailed in ref. 9) builds on previous work by others[3,4,20]. Initial results were vetted and refined through feedback from 19 nanotechnology researchers. We searched titles, keywords and abstracts using eight distinct search modules. The first search module retrieved abstract records using the term 'nano*', and then excluded records that just contained terms such as nanosecond. A second search module retrieved articles in nano-related journals, and two other modules retrieved records that contained certain terms (for example, quantum dot, molecul*, motor*). Four modules retrieved records with select terms (for example, STM (scanning tunnelling microscopy), pebbles) contingent on these records also containing terms suggestive of research at the molecular level. A study that compared our search approach with five others concluded that five of the six approaches (including ours) yield consistent results[21]. As a result of this comparison, our search strategy is being adapted by the Euro Nano Observatory to monitor the nanoliterature. We retrieved abstract records from SCI, INSPEC, EI Compendex and three patent databases. Here we analyse the 2008 subset of the SCI dataset of 572,000 nano-related publication abstracts compiled for 1991–2008 (ref. 9). The ~6,650 journals in the SCI are each allocated to one or more of 175 subject categories. (There are a further 69 subject categories in the social sciences and the humanities, and the set evolves over time.)

We use *VantagePoint* software (www.thevantagepoint.com) for data cleaning, analyses and mapping operations. Special thesauri associate cited reference sources to subject categories and macros generate the integration scores based on the similarity matrix. We set a threshold of papers having at least four cited references, and subject categories successfully associated with at least three of the references (note that the subject category can be the same for all three references). Some 39% of journals indexed by Web of Science are associated with more than one subject category.

Data are transferred to *Pajek* software (http://vlado.fmf.uni-lj.si/pub/networks/pajek) to make the science overlay maps. The labels in the science overlay maps are macrodisciplines (see ref. 14) that derive from principal components analysis (PCA) of cross-citation (bibliographic coupling) among subject categories. The set of macrodisciplines used in Table 1 was derived from PCA on the full set of 244 subject categories[18]; the macrodisciplines used in Figs 1 and 2 were derived from PCA on the 175 subject categories in the SCI (that is, they did not include the social sciences and humanities)[14]. We analyse the full 244 subject category set for completeness, but map the smaller set for higher resolution. The clustering of the subject categories in the maps is based on citation patterns. We name the resulting macrodisciplines based on our sense of the concentrations represented. The materials science macrodiscipline contains 12 subject categories, including 'physics, applied', 'physics, condensed matter' and 'nanoscience and nanotechnology' (Supplementary Table S2). ❐

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Additional information

Supplementary information accompanies this paper on www.nature.com/naturenanotechnology.