Nanoscience and Nanotechnology: Evolving Definitions and Growing Footprint on the Scientific Landscape

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"Make Everything as Simple as Possible, but not Simpler."
~A. Einstein

Introduction: Defining the Field

Various definitions of the fields of nanoscience and nanotechnology have been widely debated in the literature.[1] Despite the accusations of purists that the current liberal usage of "nano"-prefixed words amounts to "embezzlement" or "political highjacking,"[1d] understanding how researchers use these terms is prerequisite to analyzing the current influence of nanoscience and nanotechnology on long-established fields in the pure and applied sciences, and indeed the entire global scientific landscape. Journal editors have been referred to as the "gatekeepers" of their field because they collectively decide what topics are appropriate for the journals which define it.[2] Of 200+ journals which focus on nanoscience and nanotechnology,[3] dozens are now devoted exclusively to these fields (hereafter "the key journals"). The terms and concepts contained in this corpus of literature reveal the consensus definition of the field in the collective mind of thousands of editors and manuscript reviewers.

The traditional definition of "materials with at least one dimension between 1 and 100 nm" is based on the size at which many materials exhibit size-dependent characteristics not evident at bulk scales.[4] This is too simplistic, however, since such characteristics occur well outside that range for some materials. Acknowledging this fact, the scope of coverage statement for the *Journal of Nanoparticle Research* specifies a size range "… from molecular to approximately 100 nm (or submicron in some situations) …" Materials with a diameter >200 nm were termed "nanofibers" in 6 of 20 (30%) random articles from the key journals (**Table 1**, Query 1) obtained by a Web of Science (WoS) search for "TS = nanofiber*". The abstract of one states: "The average diameters of PCL/PLA/HA nanofibers were in the range of 300–600 nm…"[5] Numerous articles in the key journals refer to particles with diameters of a few hundred nm as "nanoparticles."[6] Terms on the conceptual fringe of nanotechnology—such as colloids, micro-electromechanical systems, and plasmonics—often appear without qualification in the scope of coverage statements of journals devoted exclusively to nanoscience and nanotechnology. Clearly the "gatekeepers" consider "nano-" terms appropriate for materials without any dimension below a few hundred nanometers in many cases.

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The Current Scope of Global Nanoscale Studies Today

In order to assess the true scope of nanoscale studies today, a search query was developed based on the percentage of records retrieved by individual terms, which are in the key journals. For example, all records retrieved using the term "graphene*" are relevant to nanotechnology, and 12% of them are from the key journals (SI, Table S2). The percentage declines for more ambiguous terms, such as "nano*" (~8%) or terms that are rarely, if ever, relevant, such as "nanofilter" (~1%). Based on this criterion, terms have been added to the "Georgia Tech" query.[7] (Table 1), including some additions to the exclusionary "NOT" list. These changes are discussed in more detail in the SI (Table S3).

A search of WoS using the modified query (Table 1) on 30 December 2010 yielded a continual increase in records retrieved per year, up to 87 263 (~5.4%) of the 1 642 023 WoS records for publication year, PY = 2009 (**Figure 1**). For each year, the percentage of these which were retrieved by the term "TS = nano*" increased dramatically from just 21.56% in 1991 to 80.05% in 2010 (Figure 1). Thus, searches for only "TS = nano*", which some authors still use as a proxy for the entire field,[8] severely underestimate the relevant literature from the 1990s. The conceptual terms of the query (Table 1, Queries 2–5) retrieved 5616 (90.71%) of the 6191 key journal records for PY 2009. A survey of the remaining 575 (9.29%) records revealed that most did not explicitly mention the dimensions of the materials being studied; thus, their relation to nanoscience or nanotechnology could not be determined based on the article title, abstract, or keywords. If a similar proportion of relevant articles from all other journals were not retrieved, then an additional ~8000 records for PY 2009 may have eluded the query.

Table 1. Search query developed in this study. Details of the development of this query are discussed in the Supporting Information (SI), Table S3. SO represents the source field; TS represents topics, which include the title, abstract, and keyword fields.

Query 1. SO = (ACS Nano OR Current Nanoscience OR Digest Journal of Nanomaterials and Biostructures OR Fullerene Science and Technology OR Fullerenes, Nanotubes, and Carbon Nanostructures OR IEE Proceedings Nanobiotechnology OR IEEE Transactions on Nanobioscience OR IEEE Transactions on Nanotechnology OR IET Nanobiotechnology OR International Journal of Nanomedicine OR International Journal of Nanotechnology OR Journal of Biomedical Nanotechnology OR Journal of Computational and Theoretical Nanoscience OR Journal of Experimental Nanoscience OR Journal of Nanomaterials OR Journal of Nanoparticle Research OR Journal of Nanophotonics OR Journal of Nano Research OR Journal of Nanoscience and Nanotechnology OR Nano OR Nano Letters OR Nano Research OR Nano Today OR Nanobiology* OR Nanomedicine OR Nanomedicine: Nanotechnology, Biology and Medicine OR Nanoneuroscience and Nanoneuropharmacology OR Nanoscale OR Nanoscale Research Letters OR Nanostructured Materials OR Nanotechnology OR Nanotoxicology OR Nature Nanotechnology OR Photonics and Nanostructures* OR Wiley Interdisciplinary Reviews Nano*)

Query 2. TS = (nano* or "quantum dot*" or "quantum well*" or "quantum wire*" or "molecul* motor*" or "molecul* ruler*" or "molecul* wir*" or "molecul* devic*" or "molecular engineering" or "molecular electronic*" or "single molecul*" or "coulomb blockad*" or bionano* or "langmuir–blodgett" or "coulomb-staircase" or "pdms stamp*" or NEMS or "atom* scale" or "ballistic transport*" or "DNA comput*" or "porous silicon")

Query 3. TS = (graphene* OR fulleren* OR buckyball* OR buckytube* OR (C60 not (C60 AND steel)) OR C70 OR C120 OR MWCNT OR SWCNT OR fullerid* OR fullerinol* OR fullerite* OR fullerol* OR fulleropyrrolidin* OR a*fulleren* OR b*fulleren* OR c*fulleren* OR d*fulleren* OR e*fulleren* OR f*fulleren* OR g*fulleren* OR h*fulleren* OR i*fulleren* OR j*fulleren* OR k*fulleren* OR l*fulleren* OR m*fulleren* OR n*fulleren* OR o*fulleren* OR p*fulleren* OR q*fulleren* OR r*fulleren* OR s*fulleren* OR t*fulleren* OR u*fulleren* OR v*fulleren* OR w*fulleren* OR x*fulleren* OR y*fulleren* OR z*fulleren*)

Query 4. TS = ((gadonano* OR glyconanopartic* OR heteronano* OR immunonanogold OR immunonanopartic* OR polynanocrystal* OR subnanocluster* OR ultrananocrystal* OR ultrananodiamond*) OR (("self assembl*" or "self organiz*" or "directed assembl*") AND (monolayer* or "mono-layer*" or film* or quantum* or multilayer* or "multi-layer*" or array* or molecul* or polymer* or "co-polymer*" or copolymer* or mater* or biolog* or supramolecul*)))

Query 5. TS = (((TEM or SEM or EDX or AFM or HRTEM or SEM or EELS or "atom* force microscop*" or "tunnel* microscop*" or "scanning probe microscop*" or "transmission electron microscop*" or "scanning electron microscop*" or "energy dispersive X-ray" or "X-ray photoelectron*" or "electron energy loss spectroscop*" or pebbles or quasicrystal* or "quasi-crystal*") AND (monolayer* or "mono-layer*" or film* or quantum* or multilayer* or "multi-layer*" or array* or molecul* or polymer* or "co-polymer*" or copolymer* or mater* or biolog* or supramolecul*)) OR ((biosensor* or "sol gel*" or "solgel*" or dendrimer* or "soft lithograph*" or "molecular simul*" or "quantum effect*" or "molecular sieve*" or "mesoporous material*") AND (monolayer* or "mono-layer*" or film* or quantum* or multilayer* or "multi-layer*" or array*)))

Query 6. TS = (plankton* or n*plankton* or m*plankton* or b*plankton* or p*plankton* or z*plankton* or nanoflagel* or nanoalga* or nanoprotist* or nanofauna* or nanoheterotroph* or nanophtalm* or nano*aryote* or nanomeli* or nanophyto* or nanobacteri* or nano2* or nano3* or nanog or nanos OR nanocapillary or nanochromosom* or nanoESI or "nano-filt*" OR nanofilt* OR nanoflow or "nano-flow" or nanog1 or nanog2 or nanoLC* or "nano-LC*" or "nano-liter*" OR "nano-litre*" OR nanoliter* OR nanolitre* OR "nano-mole*" OR "nano-molar" OR nanomole* OR nanomolar* OR nanosatellite* or "nano-second*" OR nanosecond* OR "nano-SIMS" OR nanospray* or "nano-spray*")

Queries 7–12. The list of ~270 organism names that begin with "nano-" (see Supporting information, Table 1).

Final search query: (#1 or #2 or #3 or #4 or #5) not (#6 or #7–12)

Current Geographic Distribution of Nanoscale Studies

For each country yielding over 500 records for PY 2010, the number of records retrieved, total 2010 country records, and percentage of total country records retrieved by the query are shown in **Table 2**. The top 5 countries by number of records were China (20 186), USA (18 472), Japan (6556), Germany (6546), and South Korea (5278). As predicted,[9] China has overtaken the USA in annual output. The percentage of all 2010 WoS records for individual countries which were retrieved by the query was stunning for several Asian countries, Singapore (16.26%), China (15.21%), South Korea (13.33%), India (11.44%), and Taiwan (11.31%), in addition to Iran (11.74%) (Table 2). This indicates a very high priority of nanoscale studies in the minds of the scientific decision makers in those countries, as has been discussed at length elsewhere.[10] The recent increase in the share of Asian journals in WoS,[11] suggests that the total literature from these countries is now more thoroughly represented in the database than in the past.

The Current Footprint of Nanoscale Studies in Materials Science, Physics, and Chemistry

Based on the WoS subject categories, the footprint of nanoscience and nanotechnology within several natural and applied science subdisciplines has recently reached staggering proportions. Dozens of the scientometric studies of this field (SI, Table S4) have examined subject category

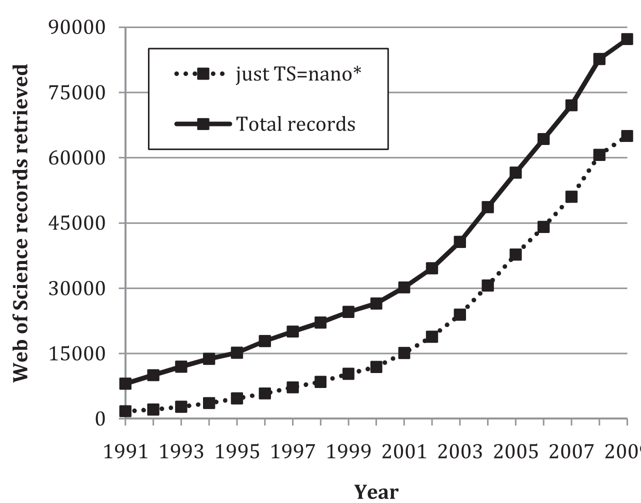

Figure 1. Records retrieved from Web of Science by the nanoscience and nanotechnology search query (Table 1). The solid line indicates the 1.8-fold increase in total database records from 1991 to 2009 relative to the number of records retrieved with the search query for 1991. Data for 2009 remain incomplete. Since ~3% of the WoS records added in calendar year 2010 were from PY 2008, it is reasonable to assume that records for PY 2009 will continue to be added in 2011.

Table 2. Geographic distribution of authorship for all countries with >500 records retrieved from Web of Science for publication year 2010.

Country	Total country records	Records retrieved by query in Table 1	% of all country records
Singapore	9324	1530	16.41
China	131 742	20 186	15.32
South Korea	40 515	5278	13.03
Iran	16 072	1892	11.77
India	40 748	4682	11.49
Taiwan	24 476	2778	11.35
Romania	6389	676	10.58
Russia	23 662	2306	9.75
Japan	77 544	6556	8.45
Germany	97 374	6546	6.72
Portugal	9571	639	6.68
France	66 727	4420	6.62
Poland	18 265	1195	6.54
Czech Republic	9068	580	6.40
Mexico	9092	578	6.36
Spain	47 957	2792	5.82
Israel	12 509	719	5.75
Switzerland	24 404	1378	5.65
Finland	10 229	550	5.38
EU-27	475 745	24 932	5.24
Austria	13 072	668	5.11
Belgium	18 504	938	5.07
Italy	56597	2806	4.96
Sweden	21 150	1041	4.92
Greece	11 424	551	4.82
USA	404 226	18 472	4.57
Brazil	31 038	1381	4.45
Denmark	12 779	543	4.25
Australia	43 526	1748	4.02
Turkey	22 558	876	3.88
England	97 784	3576	3.66
Netherlands	34 705	1266	3.65
Canada	60 912	2117	3.48

distribution among retrieved records. However, none of them have examined the proportion of articles retrieved relative to the total size of the subject categories in the WoS database. The tedious method for obtaining accurate annual subject category counts is discussed in the SI (Table S3). For the top 5 WoS subject categories among PY 2009 results, the percentages of all category records which were retrieved by the query for each year from 1997 to 2009 are shown in **Figure 2**. These percentages increased several-fold for all 5 categories: "Nanoscience & nanotechnology" (18 to 70%), "Materials science, multidisciplinary" (17 to 52%), "Physics, applied" (19 to 42%), "Chemistry, physical" (11 to 41%), and "Chemistry, multidisciplinary" (8 to 32%). Since the "Nanoscience & nanotechnology" WoS subject category includes several journals

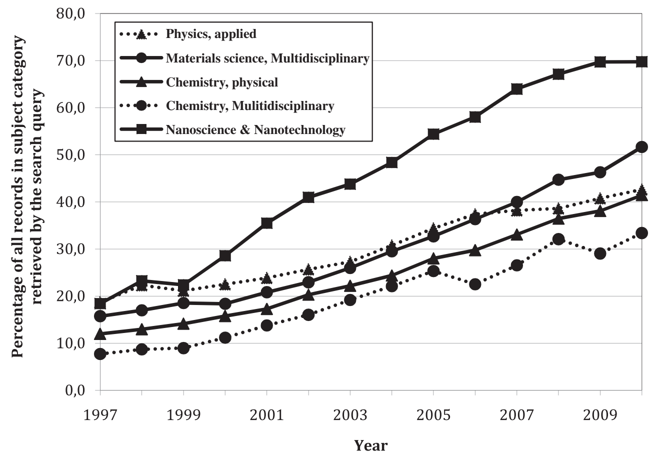

Figure 2. Percentage of all records in 5 top Web of Science subject categories which were retrieved by the search query in Table 1. These subject categories had the highest number of records retrieved by the search query for PY 2009. Because these are percentages, data for the partial year of 2010 are included. The footprint of nanoscience and nanotechnology within these fields has grown dramatically in just the past 13 years.

with "nano- to micro-scale" scopes of coverage, the query is not expected to retrieve all records assigned to this category. China's 20 186 nanoscience and nanotechnology records for 2010 (Table 2) outnumbered the 2010 WoS records for China in the broad subjects of Materials science (15 231), Engineering (17 155), or Physics (19 681), but not Chemistry (26 663). These facts underscore the massive resources being devoted to nanoscale studies in China today.

Conclusion

Semantic change is a linguistic reality. Today, "nano"-prefixed words are commonly applied to materials much larger than 100 nm throughout dozens of journals whose scope of coverage is limited to studies they define as "nanoscience" and "nanotechnology." So while the 1–100 nm criterion is convenient,[7] it is too simplistic to reflect either the scientific reality of size-dependent characteristics among all materials or the general usage of these terms. Any operational definition of "nanoscience" and "nanotechnology" should bear in mind Einstein's "… simple as possible, but not simpler" concept. Using the WoS database, the results of the query developed here indicate that in just the past 13 years, nanoscale studies have grown from once moderate to now alarming proportions of all research in certain disciplines and the scientific output of certain countries. Whether this growth will continue unabated in the future may depend on our ability to deliver concrete applications in the "post-Hype" era.[12]

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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