Realizing the Promise - The Development of Research on Carbon Nanotubes

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Realizing the Promise
The Development of Research on Carbon Nanotubes

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Abstract: The present reflection on the development of research on carbon nanotubes stems from the publication of the report "Realizing the Promise of Carbon Nanotubes" by the US National Nanotechnology Initiative in 2015. The report is a critical assessment of the state-of-art of of CNTs research and highlights some unresolved issues related with this field. Starting from the results of this assessment, we carried out an analysis of the publications' pool in CNTs and related domains, by exploiting bibliometric tools. We focused on the item of competition/collaboration between disciplines and nations, with the purpose of evaluating the position of chemistry (as a discipline) as well as the position of the main European countries and the European Union (EU) as a whole in the context of CNTs research. The results of such analysis outline very clearly the interdisciplinary landscape wherein CNTs research is situated and show the highly competitive place occupied by EU in the field.

A glance at CNTs research

Starting point of this reflection on the development of research on carbon nanotubes (CNTs) was the announcement on Chemical & Engineering News [1] of the report "Realizing the Promise of Carbon Nanotubes", released by the US National Nanotechnology Initiative on March 12, 2015 [2]. The discovery of CNTs dates back to a quarter of a century ago, and in the United States it seemed to be time to assess the state-of-art of the field. The report highlights some unresolved issues, such as production methods, quality control and scalability of CNTs production: as it is a very recent report, we refer to it for all scientific issues discussed in the present article. Aim of our research is the analysis of the multidisciplinary context that, in recent decades, has seen an impressive development of research on nanotechnology and CNTs: such development has not only been fuelled by substantial public and private investments, but also by a very strong competition at several different levels, each of which is important for a full understanding of the scientific, technological and economic interests of stakeholders involved in this type of research. The competition in the CNTs field occurs between research groups, disciplines, journals, and nations or groups of nations. We have focused our attention on the competition between disciplines and nations or groups of nations, with the purpose of evaluating the position of chemistry (as a discipline) as well as the position of the main European countries as well as the European Union (EU) as a whole in the context of CNT research. To assess the evolution along time as well as the extent of such competition we used the bibliographic data provided by Scopus, the powerful Elsevier tool that is widely employed for scientometrics [3, 4]; the Scifinder database has also been exploited for making some data cross-checks. A technical note: in the present article we will use the following notation to designate the keywords used for data mining in the Scopus database: |carbon nanotube|, |protein|, etc.

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Competition between disciplines

A first relevant point is that the interest towards CNTs is spread over many different research fields. Tab.1 shows the distribution of 67,726 articles on |carbon nanotube| - published in the 1991-2014 time range - over seven main subject areas. The last column of Tab.1 reports the number of 'disciplinary contributions', supplemented by a percentage. These percentages are calculated as ratios: [(disciplinary contributions)/(total number of articles)]x 100. They sum up to more that 100%, because each article may be pertinent to more than a single discipline; hence it may count for more than one contribution, depending on the disciplinary tags assigned to it.

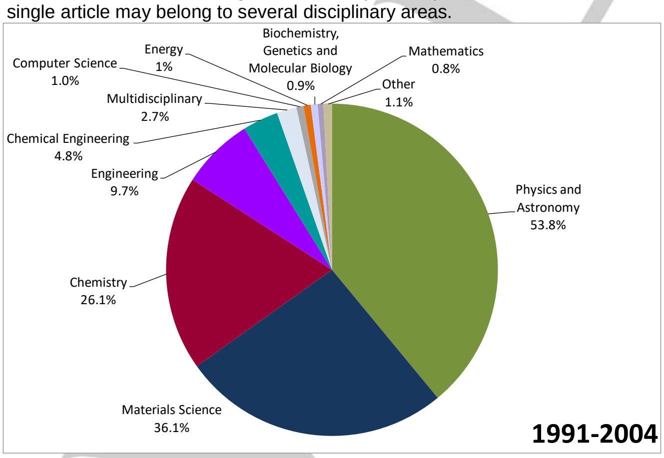
Tab. 1 Distribution of 67,726 articles on CNTs vs. subject areas (cumulative data since 1991).

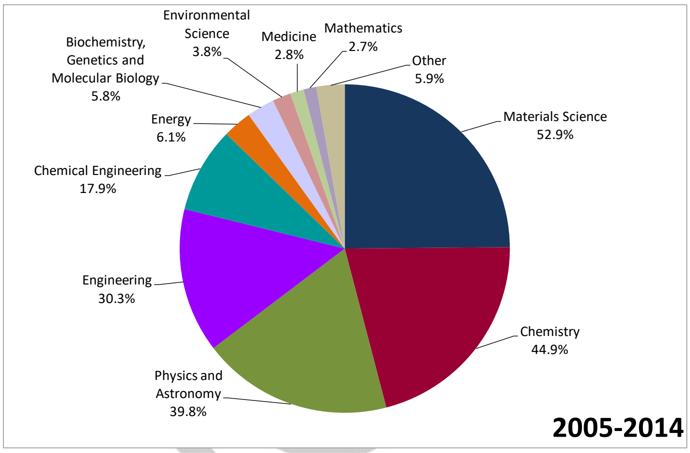
Abbreviation	Subject area	1994	1999	2004	2009	2014[a]
BIOCHEM	Biochemistry, Genetics and Molecular Biology	1	6	84	1066	3480 (5.1%)
CHEMENG	Chemical Engineering	3	68	439	3624	10917 (16.1%)
CHEM	Chemistry	25	280	2389	11666	28668 (42.3%)
ENER	Energy	1	14	88	1222	3635 (5.4%)
ENGIN	Engineering	2	95	887	6802	18627 (27.5%)
MATSCI	Materials Science	30	542	3299	14981	34294 (50.6%)
PHYS	Physics and Astronomy	77	879	4915	14842	28206 (41.6%)

[a] The overall sum of papers in the last column is higher than 67,726; this is due to the fact that SCOPUS may assign a same article to distinct subject areas, depending on the interdisciplinary character of the corresponding journals. Hence, these numbers rather count the 'disciplinary contributions' referred to 67,726 articles.

This way of treating bibliometric data may seem original, but in fact it is common, as the following quote demonstrates: “A straight publication counting method was used to count USDA-authored articles. […]. In the straight counting method, individual publications were categorized into various scientific fields or subfields by assigning them to the field of science identified by the contributing author(s) for submission to the journal and categorized by Scopus subject area. The average count of a single article is 1.56 because it may be categorized by Scopus into one or more subject areas.” [5]. Scopus associates these 67,726 articles to 15 different subject areas: the 7 areas reported in Tab.1 are the more populated ones. Data in Tab.1 show that - since the very beginning of research on CNTs - physics was not left alone, as chemistry and materials science very quickly provided important contributions to the field. Interestingly, over the years, materials science and (later) chemistry quantitatively outclassed physics. The outcomes of this competition between disciplines are clearly illustrated by Fig.1: in years 1991-2004 the items falling within the PHYSICAL area covered the 53.8% of the published contributions, whereas in years 2005-2014 the privileged position was occupied by MATERIALS SCIENCE (52.9%). Both chemistry and chemical engineering registered an impressive increase: they almost doubled in the second period with respect to the first one. A glance to the two panels of Fig.1 highlights an apparent oddity: similar percentages may result in very different areas in the two pie-graphs. This is the case of sectors PHYSICS and MATERIALS SCIENCE in the upper graph and lower graphs, respectively. Nevertheless, the absolute number of contributions in MATERIALS SCIENCE is higher than those of PHYSICS. This outcome results from the above-mentioned meaning of such percentages. A simple calculation shows that, in the 1991-2004 period, an average of 1.37 disciplinary contributions per article was found; in the 2005-2014 period this average raised to 2.13 contributions per article. In other words, these data account for a net increase in inter-disciplinarity..

Fig. 1: Distribution of articles on |carbon nanotube| over different subject areas. An impressive increase of the total amount of paper published in the field is registered: 9137 articles in the 1991-2004 time range vs. 58589 articles in the 2005-2014 time range. Percentages refer to disciplinary contributions and not to single articles: they sum up to more than 100% as a single article may belong to several disciplinary areas.





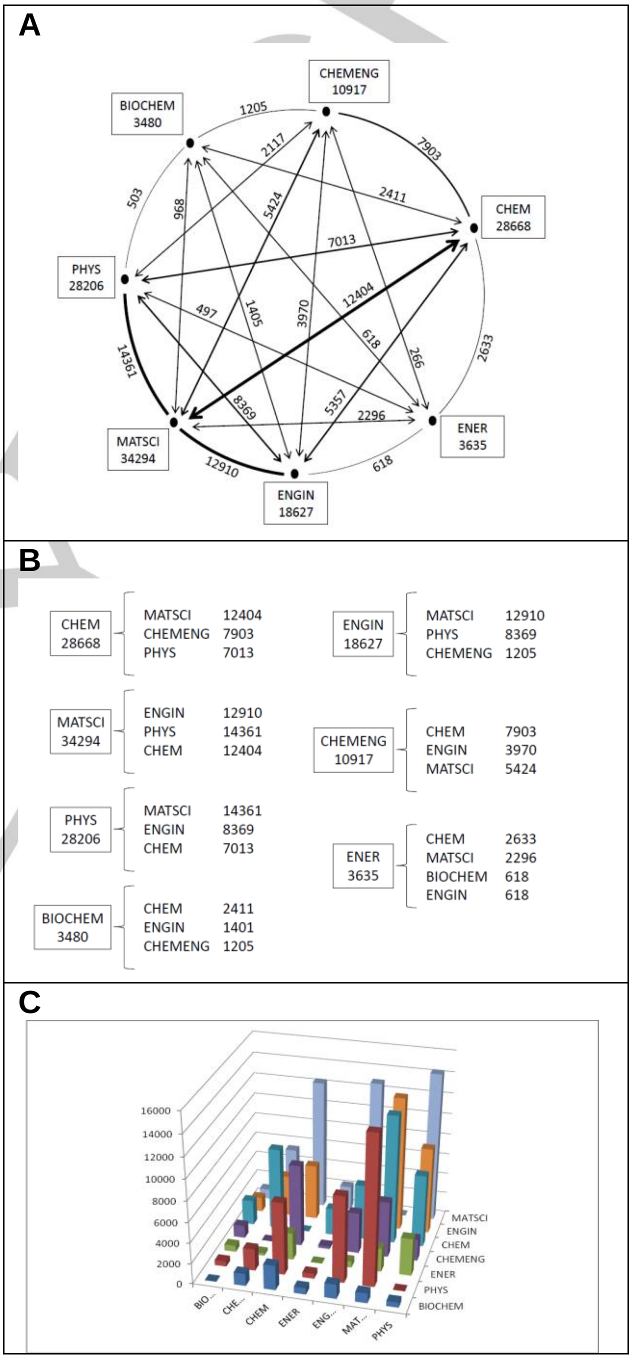
Interdisciplinarity: the collaborative network in CNT’s research

Despite the fact that a superficial analysis of the two graphs of Fig.1 may settle the relationships between disciplines in terms of a strong competition between them, a more thorough analysis of the overall data (and, in particular, data collected in the last column of Tab.1) highlights that - in addition to competition - there are also important forms of collaboration between disciplines and these forms are increasingly important. The analysis may be pushed forward.
Collaborative relationships may be highlighted for every single subject area with respect to the other: for example, overlaps between MATERIALS SCIENCE and CHEMISTRY may be found by counting the items assigned simultaneously to both areas. The most relevant outcomes of this analysis for each discipline are graphically presented in Fig. 2 A, B and C. Fig.2A clearly depicts the intense exchange of interdisciplinary relationships catalyzed by the theme |carbon nanotube|. In addition, these data witness the inherent complexity of a set of CNTs, as a material system. In fact, according to the definition of complexity proposed by the biomathematician Robert Rosen, a system is complex when the knowledge about it is obtained through research practices that are by no means reducible to each other in a formal way [6]. This is certainly the case of the mutual irreducibility of the seven subject areas reported in Fig. 2: the impossibility to assign papers on CNTs to a single discipline (e.g. PHYSICS or CHEMISTRY or MATERIALS SCIENCE) is indicative of the epistemological complexity of these systems. Another issue related with CNTs’ complexity relates with the emergent properties that stem from the architecture of these new nano-objects. The great interest in the unique properties of CNTs is proven by the increasing determination with which CNTs’ research has been carried out along the years (see Tab.1). Fig. 2B and C show the privileged binary relationships between disciplines; when considering these data in the horizon of the individual disciplines, some interesting findings come out. The interdisciplinary horizons of chemistry and physics show a high symmetry that goes beyond their mutual exchange; in fact,

both disciplinary fields favour the relationship with materials science, and engineering (chemistry relates primarily with chemical engineering and physics with engineering tout court). Materials science maintains an intense and almost quantitatively equivalent relationship with physics, engineering and chemistry; surprisingly, the only subject area that exhibit privileged relationships with both the engineering areas is the biochemical one. Another aspect of the relationships between subject areas that is not trivial emerges from Fig.2C: this is the possible asymmetry of the interdisciplinary relationship between two subject areas. For example, biochemistry has strong relationships with chemistry and the two engineering areas, but none of these three areas displays biochemistry amongst its privileged interest.

The data discussed so far are the contributions of thousands of researchers, located in the most various professional and institutional positions and represent the results of a search query. Any search query on a given keyword, made in the Scopus databases and software, automatically links research, researchers and articles related with the chosen keyword and/or research field. It depicts an objective, neutral landscape, in the sense that it is devoid of any intention. For example, a search query on |carbon nanotube| provides the interdisciplinary landscape quantified in the last column of Tab.1. These data are neutral with respect to the problems or the needs expressed in the aforementioned report of the US National Nanotechnology Initiative (namely, the quantitative and qualitative improvements of mass production of CNTs). Nevertheless, impartiality of data does not imply impartiality of interpretation. Bibliometric data collected with a specific aim may help the Scopus' users to make assessments: clearly, the evaluation is not inherent to the data; it is actively performed by the user of bibliometric data, in relation with the aim for whom data were extracted from the database. To this regard, we would like to comment an analysis that provided an amazing result. The problem of the mass production of CNTs has been analysed in-depth by the researchers of the Key Laboratory of Green Chemical Reaction Engineering and Technology of the Tsinghua University (Beijing). In 2011 they wrote an extensive review entitled "Carbon Nanotube Mass Production: Principles and Processes" [7], that appeared on ChemSusChem, a biweekly peer-reviewed scientific journal covering sustainable chemistry. The authors tackle the problem in very clear terms "Although CNTs can now be produced on the tons scale, knowledge of the growth mechanism at the atomic scale, the relationship between CNTs' structure and application, and scale-up of the production of CNTs with specific chirality are still inadequate" [7]. A review is a kind of scientific communication that is obviously important. Nevertheless, it assumes a particular relevance in our context, because not only a review endeavours to provide the most significant information on a chosen topic: it also designs a landscape of the knowledge in the field. In the quoted review, the Chinese researchers refer to 438 documents, including 55 patents (this number was deduced by comparing Scopus and SCIFinder outputs).

Fig. 2: The relationship network amongst disciplines, grown around the topic |carbon nanotube|. *Panel A*: binary relationships. The numbers associated with each arrow indicates the papers published in the 1991-2014 time range that Scopus recognizes as belonging to both disciplinary areas. Line thickness is roughly proportional to the extent of interrelationships. *Panel B*: privileged relationships occurring between disciplines (Data refers to the 1991-2014 time range.). *Panel C*: graphical representation of the privileged relationships occurring between disciplines.



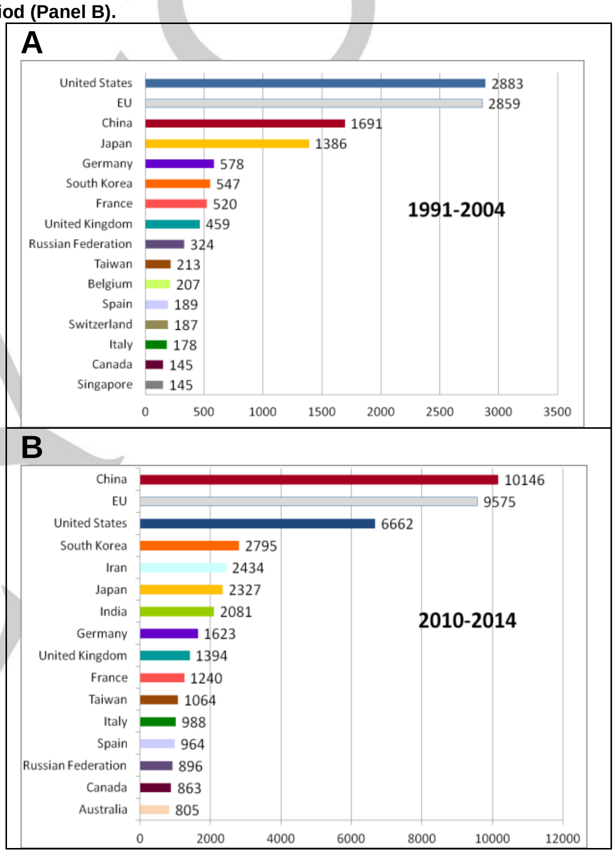
The number of 438 quoted documents is already relevant, but it soars to a giant 60,128 documents, when Scopus is asked to count the related documents which quote any of the 438 original bibliographic entries. This purely quantitative result is per se relevant, because it shows that a good 26-pages-long review summarizes – directly or indirectly – a huge amount of knowledge. Moreover, this knowledge landscape provides even more meaningful details when we take a look to the subject areas associated with these 60,128 articles: materials science (29,761; 49.5%); physics and astronomy (23,306; 38.8%); chemistry (22,877; 38.0%); engineering (17,492; 29.0%); chemical engineering (10,590; 17.6%). A comparison between these data with those of the last column of Tab.1 leads to the amazing conclusion that the Beijing team argued the same knowledge landscape that was automatically disclosed by the Scopus' server. The main difference between these data is that the Chinese investigation was performed with a clear-cut aim and the results were interpreted in the light of such intention, whereas the Scopus data as such are devoid of intentions. The two landscapes are almost coincident but it is only the researchers' intention that allows designing a road map within that landscape.

Competition between nations

Going back to the issue of competition in the CNTs research field, we may have a look at Fig. 3. Each figure panel compares the production of 15 countries plus the European Union (EU), expressed in terms of published papers on |carbon nanotube|. EU is not taken into account by Scopus, as it does not exist as an independent scientific-political entity. The EU data reported in Fig. 3 were obtained by adding the contributions of individual countries that are affiliated to the EU. In the 1990-2004 period, the United States are in the first place with 2,883 articles, followed closely by the EU (2859 items) and China (1691). In the consecutive period, China attained the first place with 10146 items, still closely followed by the EU (9575 items), while the United States is at the third place with 6662 items. This trend was already remarked by Leydesdorff et al., albeit in a different research field: "The center of gravity of the world system of science is changing; its axis appears to be moving from North America to Europe and now to Asia" [8]. Fig.3 plots suggest further reflections on the position of the main European countries. Over the years their relative positions change significantly, although they have always a place amongst the most competitive countries. Interestingly, in the later period new important actors from the East (e.g. Iran, India) gain relevant positions, and this provides an indication of the harshness of the competition in this field. By the way, these 'new entries' exceed the scientific output of Germany - the first of European countries in the list - that slips back from the fifth to the eighth position (interestingly, Germany is exceeded even by South Korea).

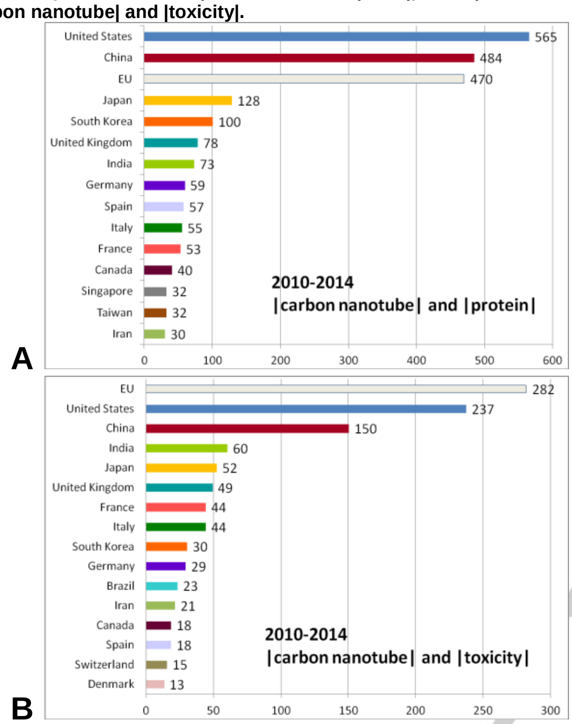
Altogether, the data presented so far show that the knowledge landscape of research on CNTs is vast, complex, and rich of interdisciplinary relationships. Within such a frame, we found interesting to have a look to the competition between nations in some more specialized sub-fields. Due to the scientific and social relevance of biomedical and health issues, we have chosen to perform a Scopus search on the keywords |protein| and |toxicity|, within the |carbon nanotube| pool of articles. In the 2010-2014 period, the published articles tagged with the keywords |carbon nanotube| and |protein| were 1040: this represents a tiny part of the overall publications on |carbon nanotube| in the same period (35348 articles). Fig. 4 (panel A) reports the distribution of these more specialized contributions over the principal nations (with EU data added to the Scopus' results).

Fig. 3: Competition between nations in terms of published papers on |carbon nanotube| in the 1990-2004 period (Panel A) and in the 2010-2014 period (Panel B).



The first three places are still assigned - although in a different order - to EU (470 articles), China (484) and USA (565). Italy is at the ninth place, after United Kingdom, Germany and Spain. Fig. 4 (panel B) - reporting the data obtained from keywords |carbon nanotube| and |toxicity| - shows a surprising scenario: EU is sharply first (with 282 articles) and Italy is at the seventh place, far beyond Germany and Spain, in a competitive position with United Kingdom and France. Of the 760 articles published in this field, 282 are assigned to EU and 237 to the United States: the gap from China (150 articles) is clear-cut. Indeed, the issues of |carbon nanotube| and |toxicity| are matter of interest for both EU and USA, with a slight advantage of the former over the latter. It is meaningful that EU decided to include nanotoxicity amongst the main research lines funded by Horizon 2020; according to recent news, published on April 27th 2015, the nanomaterials research on health risks in the United States will get a boost in fiscal 2016 year, with the allocation of about 10% of the National Nanotechnology Initiative's $1.5 billion budget to risk assessment research.

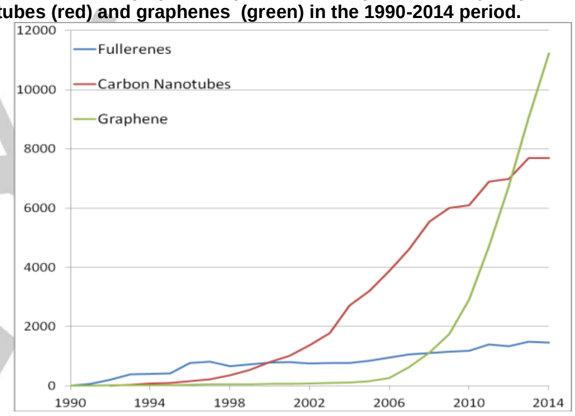
Fig. 4: Competition between nations in terms of published papers in the 2010-2014 period. Panel A: |carbon nanotube| and |protein|. Panel B: |carbon nanotube| and |toxicity|.



Conclusive remarks

In conclusion, we would like to add a few remarks as regards both methodological and more general issues related with scientometrics. The methodology followed in this paper is based on bibliometric data mining. We used Scopus for getting evidence of the extent and the disciplinary form of a collective interest towards a specific scientific object. Fig.5 clearly illustrates the relevance of intersubjective agreement of important sections of the scientific community in driving scientific research. Fig. 5 provides a graphical representation of how the interest of the scientific community towards three important items in the field of nano-objects changed along time. The reality of the 'collective agreement' is disclosed by the investments in human and instrumental resources made by thousands of researchers, who choose to work on these three specific issues and wrote papers indexed by SCOPUS. The research trends of fullerenes, nanotubes and graphene are extremely diversified. In order to contextualize these data within the whole chemical bibliometric landscape, we take into account the whole 3,202,059 papers indexed by SCOPUS as belonging to CHEMISTRY in the 2000-2014 period. This production has seen a 245% increase from year 2000 (134,247 articles) to year 2014 (328,364 articles). Year 2000 saw the interest towards nanotubes to exceed the interest for fullerenes (795 articles vs. 783). Between 2000 and 2014, the increase of the bibliographic production on fullerenes was 85%, much lower than the average of the overall CHEMISTRY production. In the same period, nanotubes saw an almost 10-fold increase (from 795 to 7695 papers, i.e. an impressive 967%). As for graphene, the collective interest became meaningful in year 2008, with 1118 articles vs. 1103 papers on fullerens, but still well below the 5546 papers on CNTs. Figure 5 shows an outburst of graphene papers between year 2008 and 2014 (a 1005% increase), while the corresponding increase of CNTs papers is only 38%. This number is below the average 47% increase of the overall chemical production in the same period, but it is beyond the 31.5% increase registered by fullerenes.

Fig.5. Annual bibliographic output concerning fullerenes (blue), carbon nanotubes (red) and graphenes (green) in the 1990-2014 period.



These data provide evidence of the variability of a research interest versus time. The scientometric use of SCOPUS data highlights several aspects of such collective and inter-subjective interest.

The results shown in the present paper demonstrate that scientometrics, even in very simple forms, is a powerful instrument as it allows to outline the interdisciplinary landscape wherein any research is situated. In case of multidisciplinary research topics, scientometrics may provide quantitative data on the evolution of the relationships between disciplines over time. It can also provide evidence of the epistemological complexity of specific research fields. It provides information on the strength and the nature of competition within a specific field. The research on CNTs has clearly been subjected to strong competition between nations (Figg. 3 and 4) as well as between research items (Fig. 5); in addition the data show that the scenery has significantly changed over time.

Another relevant scientometric output concerns EU: it is clear that the European Union is competitive with big nations such as China and United States, as far as scientific research is concerned. This occurs in spite of the political and administrative lack of coordination between the different countries of EU. The data suggest that the attainment of a stronger political and administrative integration between European nations in terms of research funding and research actions might place EU in a prominent position in advanced research fields.

At the same time, the nature of these data highlights also their limits. In fact, bibliometric evaluation may be (and, actually, it has been) employed as a powerful instrument of administration of research politics. In our analysis, we have stressed that that bibliometric data are neutral, i.e. they are not inherently politic. Nevertheless, they may become a political instrument within the perspective imposed by the stakeholders that extract information from the databases and use them. In other words, they may represent a valuable support to political decisions that - nevertheless – are actively taken by the stakeholders and remain under their full responsibility. These decisions may concern the research lines to be promoted or abandoned, but it is clear that the freedom of financing research lines that have not yet produced significant bibliometric outcomes, or that will always occupy minor positions on the basis of bibliometric parameters, must be preserved: in fact, the cultural value of a research topic cannot be assessed solely through the application of quantitative indexes.

A further aspect that deserves a comment is the statistical significance of scientometrics outputs. The bibliometric tool is conceived for handling quantitative data on a statistically significant scale. Distorsions may arise when this tool is applied to small sized research groups or domains, not to say to single researchers, in spite of the contextual use of Impact Factor data. This last case is particularly delicate, as bibliometric data might be used to promote or to stop careers whose value should rather be judged on the basis of more complex issues than the simple quantitative data, bearing in mind that those numbers conceal individuals that needs to be motivated and valorized through the creativity of their own work.

Keywords: carbon nanotube, graphene, fullerene, bibliometry, research competition.

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