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Nanotechnology innovation system: Understanding hidden dynamics of nanoscience fusion trajectories

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ABSTRACT

Nanoscience and technology has introduced a new dimension to basic sciences and a range of technologies. Researchers from various scientific disciplines are aggressively getting involved in the relevant research as a parallel way to boost nanoscience competitiveness through academic research, and corporations are directing their R&D activities towards the exploration and exploitation of nanotech opportunities. For years, it has been said that innovation is achieved by breaking through the boundaries of existing technologies. This paper has argued how nanotechnology is driven by scientific research and in what way traditional disciplines are fused into this emerging area. We attempt to provide an empirical analysis of the dynamics of nanoscience fusion trajectories, which is typically a focused area in innovation studies. In this paper, we seek to understand the attributes that are likely to enable scientific disciplines to fuse into nanoscience through a combination of quantitative and qualitative search within nanotechnology systems of innovation (NanoSI). An insight of the similarity and disparity of fusion between Europe and Japan is also provided. Finally, we develop an integrative framework to explore the co-evolutionary nature of nanotech. The paper then tries to derive some implications that would be useful for science and technology policy makers as well as for researchers in traditional scientific disciplines.

1. Introduction

Nanoscience and technology has become a very active and vital area of research, which is rapidly developing and spreading to almost every field of technology domains as well as science and engineering disciplines [1,2]. For nanoscience, it is difficult to pin down one discrete field since it is less basic science rather different lines of scientific disciplines at nano-scale where the classical laws of basic science do not readily apply. On the other hand, nanotechnology is not confined to one industry rather an enabling set of technologies that cut across versatile industry sectors [3]. Probably uniquely, nanotech is classified by the size of the materials being developed and used, not by the processes being used or products being produced [4]. Nanotechnology is widely considered as being such a general-purpose technology and becomes a common technology for almost all technology sectors because of its ability to create super-functional properties of materials at nano-scale [5]. Due to nano-dimension, it transcends the conventional boundaries between scientific and engineering disciplines and technology sectors. Specifically it has predicted that the aggressive growth of IT and biotechnology cannot be sustained without nanotechnology [6]. In a sense, nanotech is likely to be the foundation for achieving widespread benefits, including smarter electronics, improved health, advanced agriculture and cleaner sources of energy [7].

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Nanotechnology has been recognized as a promising new growth innovator for the decades to come [8–10]. Additionally, Wonglimpiyarat proposes that nanotech is entering the sixth Kondratieff by nano-engineering and manufacturing [11], likely to bring revolutions in research and technology arenas.[1] This, however, raises the question of either one can expect a new type of technical change? The source of new nanotech paradigms, which can explains the main sources of technical change, is coming from fundamental advances in nanoscience. Hardly any other sector has attracted so much public and private funding globally as fast, and thus encouraged a dramatic rise in research and development in all developed countries and many developing countries. Organizations (e.g., universities, public research institutes and industry R&D laboratories) are strongly focuses on nanoscience and technology recently to grasp competitive scientific and technological advantages.

For years, it has been said that innovation is achieved by breaking through the boundaries of existing technologies. Therefore, technology fusion [12,13] related to nanotech stands a significant importance in technology management and innovation studies since the field is so diverse and affects a versatile disciplines and sectors. However, technology fusion demands intensive research to understand the interaction of information, material, and energy at the most basic levels including the atomic and molecular. Nanotechnology, as a case, offers a significant opportunity to analyze due to its nano-dimension, which operates in the atomic and molecular scale. We assumed nanotech is a highly multi-disciplinary fused technology. Both, gaps in the literature and the government-prioritized initiatives of nanotech reveal a need for exploring and implementing nanotechnology innovation system (NanoSI), and thus make it an excellent case of study. This paper aims at closing this gap by making major contributions in the areas of technology fusion and practice within NanoSI. It has argued how nanotech is driven by scientific research and in what way traditional disciplines are fusing into this emerging area and what are the determining factors. The central purpose of this paper is to provide an empirical analysis of the dynamics of nanoscience fusion trajectories, which is typically a focused area in innovation studies. We focus on the discourse development of traditional science disciplines (nano-scientific output share, citations over time and link with each discipline) and attempt to establish the pattern of science disciplines' knowledge fusion into nanotech. The following analysis then identifies the concerned factors driving nanoscience fusion in the case of Europe and Japan. The embryonic fluid stage of NanoSI represents a methodological challenge conceptually as well as data wise. A hybrid research method adopts by utilizing both quantitative and qualitative search, which creates a more solid foundation to synthesize nanoscience fusion trajectories within NanoSI.

2. Theoretical and conceptual framework

Nanoscience and technology is now penetrating into a range of scientific disciplines and technology sectors. For structuring and interpreting the roles and linkages within nanotechnological system as well as to visualize the dynamics of NanoSI, the framework of Techno-Economic Network (TEN) provides a useful approach, as illustrated in Fig. 1. The concept of TEN put forward by Callon and Bell [14], which provides a basic and simple analytical framework to analyze the systems of innovation in a comprehensive manner (practical applications of the framework to selected industries, e.g., [15] on robotics; [16] on software). Since it is widely accepted that innovation is a complex interactive process [17,18] involving disparate actors and activities, the TEN concept can broadly analyze such a system. The term TEN is developed as an approach to specific cases: either studies of particular innovations or the organizational arrangements within which particular innovative activity is intended to take place, an approach which is applicable to all kinds of innovation: failed or successful, radical or incremental [19].

TEN has been organized around three major ‘poles’[2] (such as Science, Technology and Market poles: these poles play a direct role in the innovation process) and another minor pole (such as finance pole: mostly indirectly play a considerable supportive role in the innovation system), each of which are defined by the type of ‘intermediaries’ circulated by the actors of the network. The intermediaries, which include explicit knowledge or disembodied information (publications, patents, reports etc), embodied knowledge or technical artifacts (technical objects like machines, instruments etc), tacit knowledge or skills and expertise (experienced personnel mobility, informal contacts etc) and money (financial credits etc), link the actors and activities internally and externally. One of the prime advantages of the TEN model is that the system of innovation can be analyzed within this framework in a flexible and dynamic way without losing its main ideology. In search of a comprehensive model, we found the TEN model which provides a simple, comprehensive and flexible conceptual framework. Nanotechnology is currently positioned just prior to or at the beginning of commercialization stage or hardly commercialized. In this study, therefore, we effectively utilize the TEN framework to analyze nanotech fusion trajectories within NanoSI, focusing Science pole where academic publications and citations related to nanoscience are regarded as viable scientific output indicators as well as Technology pole where qualitative data on nanotech R&D systems (retrieved through face-to-face interviews) stand a significant input to analyze.

On the other hand, the concept of systems of innovation (SI) [17,18,20–23] has attracted mainly to the belief that it represents a promising conceptual and analytical tool for better understanding innovation process. The SI approach can been applied to different levels of the economy depending on whether one is trying to analyze or promote innovation at national, regional or sectoral level. Leaving these levels, Carlsson et al. [24,25] came up with technological system, which is defined as a network of agents interacting in a specific technology area under a particular institutional infrastructures or a set of infrastructures and involved in the generation, diffusion and

[1] The key factors in the identified former 5 Kondratieff's being: 1) cotton for textile innovation, 2) coal and iron for steam power and railway innovation, 3) innovation in industries based on electric power and steel, 4) oil for innovation in automobiles and synthetic materials, and 5) chips (microelectronics) for information, communication and computer networks.

[2] The *scientific* pole consists of universities, and public and private independent research centers, which produces empirical knowledge. The *technical* pole consists of technical labs in firms, cooperative research centers and pilot plants, which design, develop and transform artifacts for specific purposes e.g. models, prototypes, pilot projects, patents, tests, standards. The *market* pole contains users, professionals and practitioners.

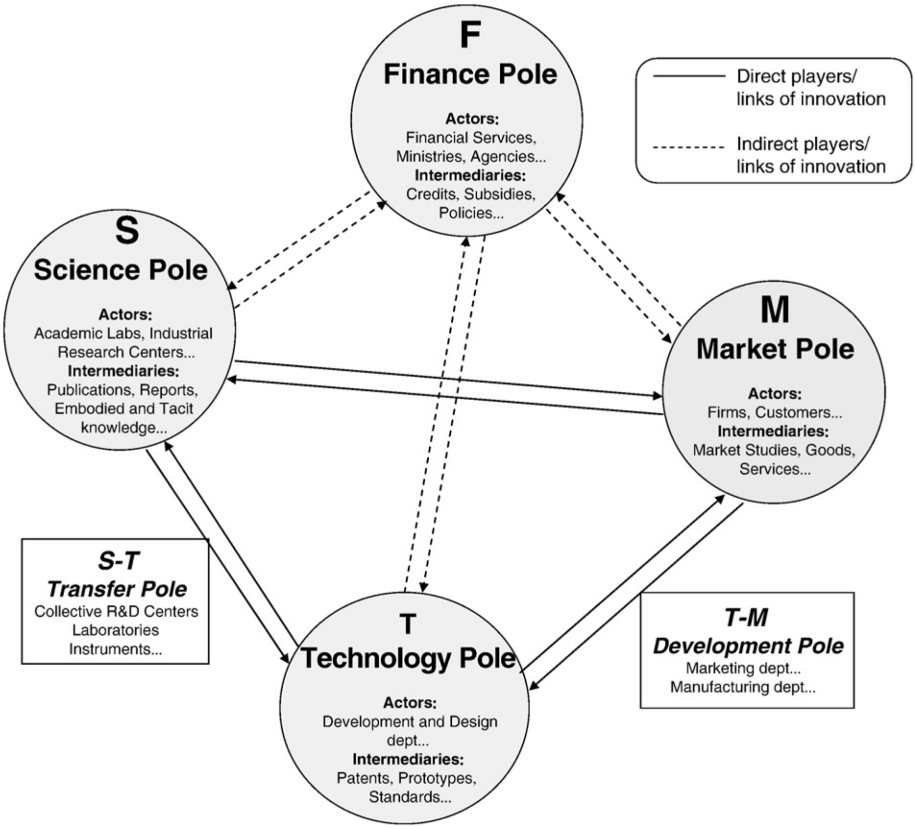

Fig. 1. Techno-economic network framework (based on Callon).

utilization of technology. The technological systems approach has a sectoral rather than a national focus. It emphasizes the inter-dependences between micro units (such as universities, research institutes, firms) on the one hand and entire sectors of the economy on the other hand. Since the national innovation system (NSI) is based on national boundaries, technological differences determine the boundaries of technological system. Carlsson et al. stressed the increasing importance of the international dimension of technological systems since innovative activities are tending to become more global. As a technology, nanotech is an emerging field and characterized by multi-disciplinary type that has an impact on various technologies. NanoSI thus does not center exclusively on national or technological factors, as for example in the SI approach, which identifies both national and technological or sectoral aspects as determinants of SI. Therefore, *NanoSI can be thought of as a complex system of different science and engineering disciplines and technology domains at nano-scale; comprised by a set of actors engaged in the development, diffusion, and utilization of the technology; linkages among actors (inevitable due to its multi-disciplinary nature) which particularly focus on a nanotech domain (such as nanomaterials, nanoelectronics, nanobiotech, nanomanufacturing and tools etc), having research collaborations and exchange mechanisms.* In addition, NanoSI interprets as a dynamic process that changes pattern over time involving multiple interacting and co-operating actors.

Several scientometrics studies have carried out on nanoscience and technology, such as Leydesdorff's study with an analysis of China's performance in nanoscience [26] focused on journal–journal citation relations particularly in nanotech journals; Meyer's bibliometric analysis [27] revealed S–T linkage between patents and publications; Hullmann and Meyer's study [28] delineated nanotech from the so-called nanoscience. Different reports such as Roco and Bainbridge [29] and Nordmann [30] emphasize that the realization of the potential of nanotechnologies is based on the convergence of technologies. Some studies seek to understand the processes that determine the productivity of authors and inventors in new technology, as measured by counting of articles and patents [31–33]. In addition, bibliometric quantification has provided an effective way to show the emergence and development of a new technology [2,26–28,34–36]. However, less studies have addressed nanotech innovation context [11,37–39]. This study relates to a concerned research of technology fusion [12,13] which was focused on combining existing technologies into hybrid technologies and blending incremental technical improvements from several previously separate fields of technology. There are no relevant studies on how an inter-disciplinary research area such as nanoscience is formed and how traditional disciplines are fusing into this area, which would be an important part to focus within SI framework.

3. Data capture and research method

Data sources are generally selected to analyze the Science pole related to nanotech. In the TEN model, publication activities are considered as one of the main activities to represent the Science pole for the analytical purpose. We use the SCI-EXPANDED database of ISI web of science, one of the most representative collections of peer-reviewed traditional scientific and technical articles, aggregating article abstracts from almost all journals. It is evident that volumes of nanoscience article increases slowly since the early 1990s to the late 1990s and increases rapidly since the early 2000s [35,36]. In this study we use a period of 5 years (2000 to 2004) begin with 2000, as the date that nanoscience publications began to be exponential. In our research nanoscience articles retrieved through queries based on specialist keywords[3] derived from the Nano Science and Technology Institute (NSTI) publications. Variations were included to encompass alternative term forms (e.g., carbon nanotube, carbon-nanotube, carbon-nanotubes) and stemming was used (e.g., nano* where the asterisk captures any word ending). Since nanoscience is a multi-disciplinary field and covers a large amount of research activities, a traditional scientific database covering multi-disciplinary fields would be a better choice in this case. The main assumption here is that actors in the Science pole including universities, public research institutes and companies usually publish their scientific achievements in various related journals. Thus assessing the publications will help to trace the activities in Science pole. The empirical analysis is followed by descriptive statistics based on a series of interviews with the representatives (scientists and researchers) in the universities, public research institutes, government ministries and funding agencies to trace the activities in Technology pole. We conducted face-to-face interviews based on structured questionnaires with nanotech academic scientists and researchers from different organizations in Europe (visited universities and public research institutes in UK, Germany, France, Italy, and Switzerland) and in Japan (visited universities and public research institutes in Tokyo, Osaka, Hiroshima, Fukuoka, Tohoku and Tsukuba, as well as government agencies such as METI and funding agency such as NEDO). We then provide descriptive statistical technique that will assist us to investigate the relevant factors of nanoscience fusion trajectories.

The increased funding has been available over periods in nanoscience and technology research since it is a prioritized area worldwide including the US, several countries in Europe (such as Germany, France, UK and Italy) and in Asia (such as Japan, China, South Korea, Taiwan and Singapore). General disciplines that were not getting much funding earlier, now have prioritized nanoscience research for taking advantages of the increased funding as well as re-labelled the research topic what they do as nanoscience rather than general disciplines such as chemistry, physics, material science, biology. It can be argued that to analyze the effect of re-labelling by the term 'nano' from the traditional discipline based on previously separate scientific streams of activity would be meaningful (e.g., are nanotech researchers or scientists doing anything different from what they did 10 years ago or did they just re-classify or re-label themselves?). Often this is a part of the process of forming a new discipline, which looks like a strange multi-disciplinary base that initially a bundle of research activities. Over time though scientists become more sophisticated, they develop their own techniques, concepts, theories, paradigms and may be a few decades later we certainly realize that we have a new discipline such as nanoscience[4] (e.g., if we look at the history of science subjects like biochemistry showing its distinctive activity by merging chemistry and biology). Therefore, there is a need to understand nanoscience fusion pattern through traditional science disciplines.

The questions addressed here as follows: how nanoscience is driven by traditional scientific research and in what way different fields are exploring and fusing into it and what are the determining factors behind it? Nevertheless, it was also our concern how we could measure nanoscience fusion. In terms of fusing disciplines together, a number of approaches we have considered: i) Searching for nano-scientific output of journals of general disciplines categorized by ISI using both Essential Science Indicator and Journal Citation Reports in terms of publications (analyzing to what extent were nanotech papers coming from scientific disciplines such as physics, chemistry, material science, biology and how it has changed over time); ii) To look for nano-related papers in each discipline at present, 5 years ago as well as 10 years ago and their reference citations (analyzing what they cite and classify the citing references into different disciplinary journals categorized by ESI and JCR classification scheme and what proportions were coming out or linking with each discipline); iii) Search for relevant factors that drive nanoscience fusion; iv) To look for institutional addresses of academic researchers (e.g., are they still located in the departments called chemistry, physics etc or are they in new inter-disciplinary research centers related to nanoscience and technology? analyzing then what proportions are in the old disciplined-based departments and what proportions are in the new named centers called nano IRCs). The analyses were performed through a combination of quantitative and qualitative search. In quantitative search, we drew upon the SCI-EXPANDED database over the period of 1995 to 2005 at 5 years interval. We have selected top ranked twenty-five journals of each discipline (such as chemistry, physics, material science, biology) categorized by ESI and JCR in terms of publications. In the period of 1995, 2000 and 2005, we have analyzed nano-related papers citation among the set of journals from each discipline. We have also classified their reference citations into chemistry, physics, material science, biology, multi-disciplinary science and nanoscience journals and facilitated the subsequent analyses. We then utilized descriptive statistics to analyze our data based on face-to-face interviews with nanotech academic scientists and researchers from universities and public research institutes in Europe and Japan.

4. Trend of nanoscience fusion through multi-disciplines

The research findings start with a general analysis of categorization of all nanoscience articles into scientific disciplines. Fig. 2 presents the total volume shares of identified nanoscience publications over three periods of 1990–1994, 1995–1999

[3] The keywords included among others: nano*, fullerene, carbon nanotube, plastic nanocomposites, quantum dot, biological nanosensor, targeted nano-therapeutics etc.

[4] Interview with Professor Ben Martin, Former Director of SPRU, University of Sussex.

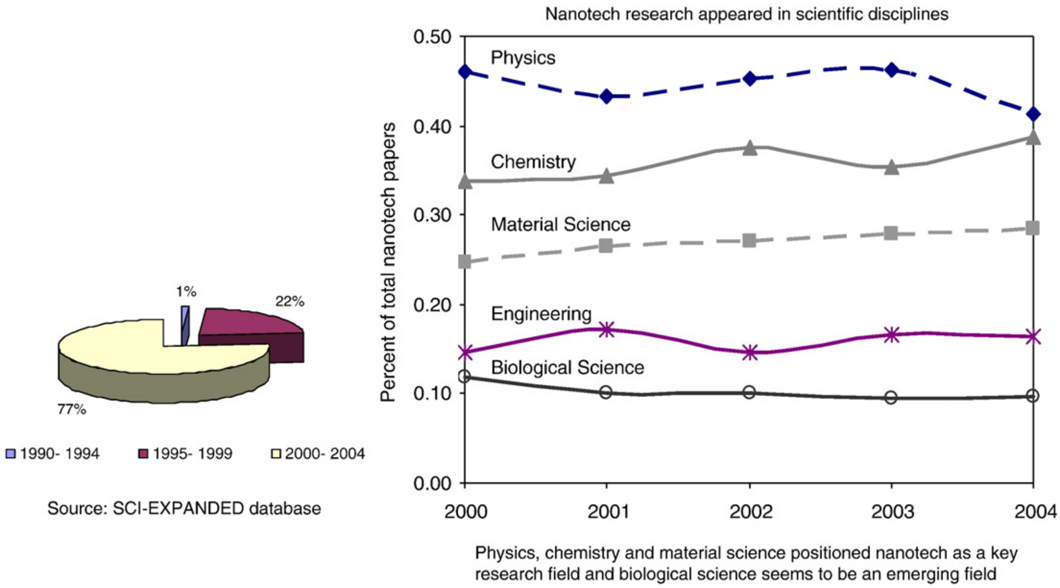

Fig. 2. Share of nanotech research output in scientific disciplines.

and 2000–2004. The early 1990s accounts for 1%, the late 1990s accounts for 22% and the early 2000s accounts for 77% of all articles. The rapid growth of publication share comes from the period of 2000 to 2004, which we have considered to show the fusion trend. We have compared their relative share distribution within each discipline over the period 2000–2004, as illustrated in Fig. 2. The findings clearly indicate that nanotech-related research plays a significant role in covering broad scientific disciplines, accounting for above 40% of all nanotech academic articles in physics, around 40% in chemistry, 30% in material science, 15% in engineering disciplines and 10% in biological science. The fields vary in the relative importance of nanotech research for academic activities with physics, chemistry and material science positioning nanotech as a key research area (over one-third of all nanotech articles) and biological science is lagging behind which seems an emerging field for nanotech.

4.1. Chemistry discipline

Firstly, we have investigated nanoscience fusion trend in the case of chemistry discipline. Fig. 3 demonstrates the overall shares of nanoscience articles in the chemistry discipline authored in the respective set of journals. We subsequently compared the output with chemistry journals' share indexed by SCI. When compared with other chemistry journals the volumes of nanotech-related articles appeared to be substantial in ten journals (such as JOURNAL OF THE AMERICAN CHEMICAL SOCIETY, JOURNAL OF PHYSICAL CHEMISTRY B, ANALYTICAL CHEMISTRY, ANGEWANDTE CHEMIE INTERNATIONAL EDITION, CHEMICAL COMMUNICATIONS, CHEMISTRY A EUROPEAN JOURNAL, CHEMISTRY LETTERS, JOURNAL OF CATALYSIS, LANGMUIR, JOURNAL OF THE ELECTROCHEMICAL SOCIETY) out of twenty-five. Nanotech publication volumes have been increasing rapidly in different areas of chemistry research (such as physical, analytical, electrochemical, catalysis etc). This growth corresponds to the extent of nanoscience research fusion and its growing importance for chemistry disciplines. The percentage share of nanotech papers indicates their significant value of basic chemistry research, since the R^2 value of those chemistry journals are relatively substantial (almost all journals output represented in the figure). It should however be noted that the position in the science pole of the techno-economic network [14] cannot merely be measured by the number of publications, but also by their importance for researchers and practitioners – citations and commercial impacts – and additionally by aggregate national R&D expenditures on an emerging technology.

4.2. Physics discipline

The annual shares of nanoscience articles in physics discipline authored in the respective journals have shown in the Fig. 3. Then we compared the output share of physics journals indexed by SCI. The volumes of nanotech-related articles appeared to be substantial in nine journals (APPLIED PHYSICS LETTERS, SOLID STATE COMMUNICATIONS, JOURNAL OF PHYSICS CONDENSED MATTER, PHYSICA B CONDENSED MATTER, JOURNAL OF PHYSICS D APPLIED PHYSICS, SOLID STATE ELECTRONICS, SEMICONDUCTORS, CHEMICAL PHYSICS LETTERS, TECHNICAL PHYSICS LETTERS, and APPLIED PHYSICS LETTERS) out of twenty-five when compared with other physics journals. Nanotech publications volumes have been also increasing rapidly in different areas of physics research (such as condensed matter, solid-state electronics, semiconductors

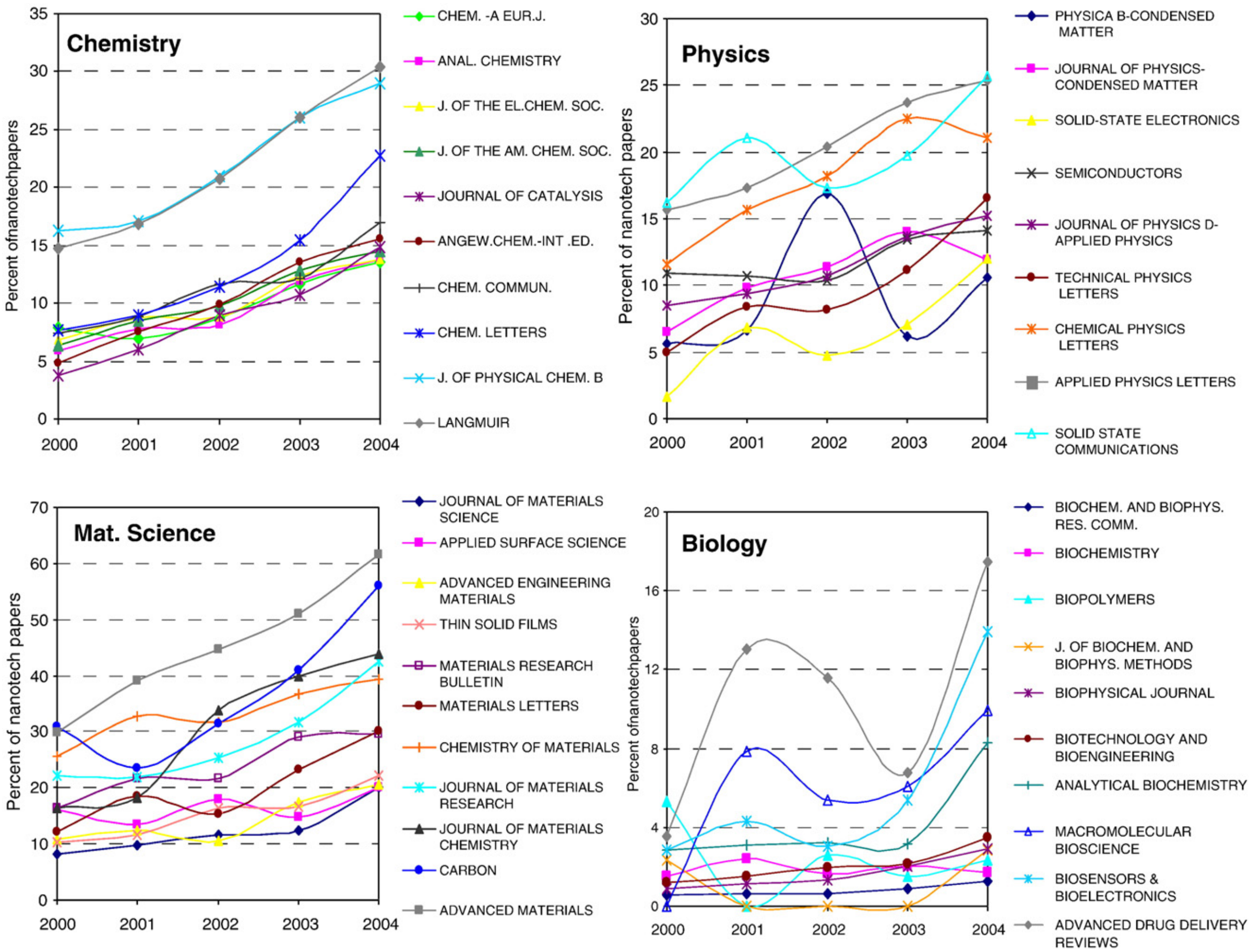

Fig. 3. Nanoscience fusion trend in multi-disciplines.

etc). This growth corresponds to the extent of nanoscience research fusion and its growing importance for basic research in physics discipline.

4.3. Materials Science discipline

In the case of material science discipline, the shares of nanotech articles authored in the respective journals have shown in the Fig. 3. We then compared the output with material science journals' share indexed by SCI. The volumes of nanotech-related articles appeared to be substantial in eleven journals (ADVANCED MATERIALS, ADVANCED ENGINEERING MATERIALS, CARBON, JOURNAL OF MATERIALS RESEARCH, THIN SOLID FILMS, MATERIALS LETTERS, JOURNAL OF MATERIALS CHEMISTRY, JOURNAL OF MATERIALS SCIENCE, MATERIALS RESEARCH BULLETIN, CHEMISTRY OF MATERIALS, and APPLIED SURFACE SCIENCE) out of twenty-five. Nanotech publications volumes have been increasing rapidly in different areas of material science research (such as thin films, surfaces, carbon material etc) rather than other disciplines. This growth corresponds to the extent of nanoscience research fusion and its growing importance for basic research in material science. The percentage share of nanotech papers in this field indicates its significance value, since the R^2 value of those material science journals are relatively substantial (e.g., advanced materials, chemistry of materials, carbon) as illustrated in the figure.

4.4. Biology discipline

Fig. 3 also demonstrates the shares of nanotech articles in the biology discipline authored in the respective journals. We then compared the output with biology journals' share indexed by SCI. The volumes of nanotech-related articles appeared to be substantial in a few journals (such as BIOSENSORS AND BIOELECTRONICS, BIOTECHNOLOGY AND BIOENGINEERING, MACROMOLECULAR BIOSCIENCE, ADVANCED DRUG DELIVERY REVIEWS, ANALYTICAL BIOCHEMISTRY) that were much less when compared with other disciplinary journals. Nanotech publications volumes have been increasing slowly in different areas of

Table 1
Scientific disciplines' fusion into nanotech in the materials domain

Domain	Search string	Search period	Nanoscience papers form science disciplines' journals	Share of cited references appearing from scientific disciplines						Trend of nanoscience fusion
				Chem	Phy	Mat Sci	Biol	Multidis	Nano Sci	
Nanomaterials	nanocrys*, nanotub*, fullerene*, nanostruc*, nanocompos*, nanomat*, nanocat*, nanofib*, thin film*, dendrim*, nano* and polymer*	1995	Chem	**64.47**	10.42	7.33	4.63	11.96	1.15	Less fusion with multi-disciplines
			Phy	11.11	**74.39**	4.34	0	8.21	1.93	
			Mat Sci	26.08	19.92	**39.02**	0.4	12.65	1.89	
			Biol	23.19	7.21	0	**54.12**	12.88	2.57	
		2000	Chem	**56.76**	12.05	15.05	5.04	10.25	0.81	
			Phy	9.06	**51.1**	5.13	0	33.36	1.32	
			Mat Sci	24.99	13.07	**35.76**	0	25.77	0.4	
			Biol	26.38	4.18	7.34	**50.79**	9.62	1.67	
		2005	Chem	**40.65**	13.26	19.93	8.86	11.04	6.23	Relatively high fusion with multi-disciplines
			Phy	16.05	**53.71**	8.07	1.13	12.9	8.11	
			Mat Sci	22.29	18.87	**29.15**	1.15	16.95	11.47	
			Biol	35.57	10.03	5.21	**36.02**	8.6	4.54	

Basis of Analysis — Selected top ranked journals in each discipline classified by Essential Science Indicators (ESI) and Journal Citation Report (JCR).
Search Method — Specific keywords derived from the Nano Science and Technology Institute (NSTI) publication.

biology research (such as drug delivery, biosensors, biotechnology etc). This slow growth corresponds to the low extent of nanoscience fusion trend. It is indicative that biological science is still an emerging field for nanotech research. The percentage share of nanotech articles of this field is too small to compare with other disciplines, revealing its weak strength right now but likely to be promising in near future.

5. Nanoscience fusion trajectories

We then wished to investigate nanoscience fusion trajectories through traditional science disciplines in the case of two important and major domains such as materials and electronics.[5] In the period of 1995, 2000 and 2005 we have analyzed nano-related papers citation among the set of journals from each discipline. We have classified their reference citations or reference linkages into chemistry, physics, material science, biology, multi-disciplinary science and nanoscience journals categorized by ESI and JCR to establish the pattern of fusion. As demonstrated in Table 1, for materials domain, it has indicated that each discipline's citing references were strongly linked with the respective disciplines 10 years ago (1995) instead of fusing with other disciplines. This trend has changed over time and at present (2005), nanotech knowledge is fusing across disciplines (i.e., focusing multi-disciplines' linkages). In the case of chemistry discipline, the share of cited references from chemistry related journals was 64.47% in 1995, and has dropped to 40.65% in 2005. In the case of physics, material science and biology, the share has dropped from 74.39% to 53.71%, 39.02% to 29.15% and 54.12% to 36.02% respectively. On the other hand, the share of cited references from other disciplines has grown since last 10 years period and balanced the gap. This result indicates that nanotech research in chemistry seems to have fused relatively within materials sciences and biology disciplines, and to a lesser extent in physics discipline. Nano-research in physics seems to have fused within materials sciences and biology disciplines, and to a lesser extent in chemistry discipline. On the other hand, nanotech research in material sciences seem to have fused within multidisciplines and nanosciences, and to a lesser extent in other disciplines. Nano-research in biology seems to have fused relatively within chemistry and material sciences disciplines, and to a lesser extent in physics discipline. It seems that in the earlier period, every discipline had less need to share nanotech knowledge or link with other disciplinary knowledge, but rather this trend has changed recently in the materials domain. With the evolution of nanotech, the basic research trend by disciplines has been changing over time from a more separate disciplinary base to a more multi-disciplinary type (i.e., moved from a system or a culture of specific fields or topics into something that is mixing at nano-scale). This may have been caused by the introduction of new nanomaterials such as carbon nanotubes, fullerene as well as rapid development of nano-instruments (such as STM, AFM etc) to control and manipulate materials at nano-scale. It can be forecasted that nanoscience fusion will be completed in materials domain in future, as illustrated in Fig. 4.

For electronics domain, the same trend appears but shows relatively more strong fusion across disciplines at present. For example, in the case of chemistry journals, the share of cited references from chemistry related journals was 67.85% in 1995, but the share has dropped to 37.26% in 2005. In the case of physics, material science and biology disciplines, it has dropped from 77.69% to 43.16%, 53.26% to 33.69% and 61.65% to 34.11% respectively. On the other hand, the share of cited references from other disciplines has grown since last 10 years period and balanced the gap (Table 2). This result indicates that in electronics domain, nanotech research in chemistry seems to have fused greatly within materials sciences and biology disciplines, and to a lesser extent in physics discipline. Nano-research in physics seems to have fused within chemistry, materials sciences and biology disciplines. On

[5] We have characterized four nanotechnology domains in our earlier research such as nanomaterials, nanoelectronics, nanomanufacturing and tools, and nanobiotechnology by using Engineering Index (EI) code defined by Elsevier Compendex. For every domain, detailed lists of relevant EI codes were identified — specific domains corresponded in general to distinctive EI classes (bionanotechnology: EI code 4.×, nanoelectronics: EI codes 6.× and 7.×, nanomaterials: EI codes 5.× and 8.×, nanomanufacturing/tools: EI code 9.×).

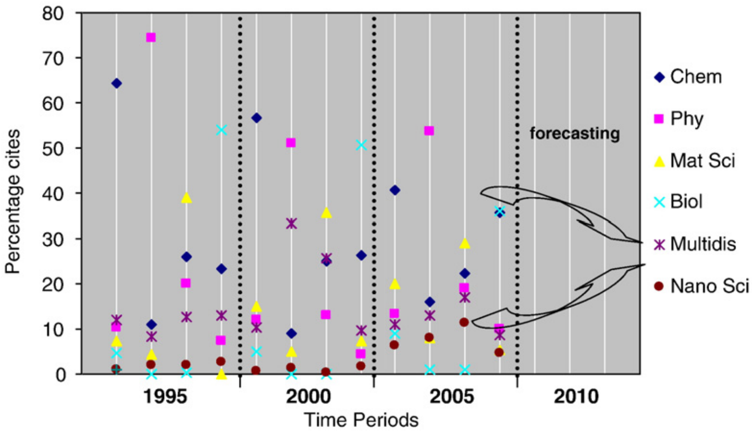

Fig. 4. Forecasting of nanoscience fusion in the materials domain.

the other hand, nanotech research in material sciences seem to have fused within chemistry and biology. Nano-research in biology seems to have fused relatively within chemistry and material sciences disciplines, and to a lesser extent in physics discipline. Therefore, it can be indicative that nanoscience evolution derives from taking advantages of scientific opportunity, which could allow researchers to undertake or share multi-disciplinary research by utilizing nano-tools. In the earlier period researchers linked with their respective disciplines' research due to lack of much instruments, but now the trend has changed having much scope of utilizing techniques to explore unfocused areas. Researchers are more interested or have to interact with researchers from other disciplines to share their expertise or knowledge to uptake more efficient outcome through nanotech. In addition, this only happens as a multi-disciplinary approach, trying to break down of the boundaries of all scientific disciplines. It can also be forecasted that nanoscience fusion will be completed earlier in electronics domain than materials, as illustrated in Fig. 5.

6. Exploring the factors of fusion

Having analyzed in detail the extent and trend to which nanotech research is fused with multi-disciplines such as chemistry, physics, material science and biology over the period from 1995 to the end of 2005; we are now in a position to explore the relevant factors of nanoscience fusion trajectories. For this, we provide descriptive statistical technique to summarize the results based on interviews conducted with nanotech scientists or researchers from universities and public research institutes in Europe as well as in different prefectures of Japan. These extensive interviews enable us to understand why nanoscience fusion trajectories arose and evaluate the extent and trend to which these are reflected by quantitative analysis in the previous sections.

6.1. The case of Europe

Most of the European scientists believe that nanoscience enables people to move from a system of specific areas into something that is a bridge of multi-fields at nano-scale. In this sense, one expert from one field may crosscut with another expert and develop some cross-linkages, help moving very separate disciplinary system into a more homogeneous system. The trend of nanoscience fusion emphasizes in converging all scientific disciplines since it is an interface of all disciplinary fields due to nano-scale dimension. Some experts believe that the starting point for such fusion is scientific opportunity that could begin to address a new system (e.g., biological system for physicists, engineers etc).[6] Therefore, it would be a very real scientific opportunity to begin fusing disciplines by coming together and taking elements from each of the discipline. Another important factor appears in Europe to have been the re-labelling research topic, because it is quite fashionable now a day to pull funding for nanoscience research by traditional disciplines in this competitive age. The other indicative point would be a study of new nanomaterials with their novel properties and function as well as new applications, and the development of techniques to observe, manipulate and fabricate nanostructures. In addition, academic scientists and researchers from general disciplines are re-located to several IRCs to explore nanoscience significantly. We have utilized descriptive statistics to explore the relevant factors of nanoscience fusion and provide our findings in the form of a spider graph, as illustrated in Fig. 6.

6.2. The case of Japan

On the other hand, Japanese scientists mostly believe that nanotech has an ability to drive research in multiple disciplines, as no boundary exists between traditional disciplines such as physics, chemistry, material science, engineering and biology at

[6] Interview with Professor John Ryan, Director of IRC Bionanotechnology, University of Oxford.

Table 2
Scientific disciplines' fusion into nanotech in the electronics domain

Domain	Search string	Search period	Nanoscience papers from science disciplines' journals	Share of cited references appearing from scientific disciplines						Trend of nanoscience fusion
				Chem	Phy	Mat Sci	Biol	Multidis	Nano Sci	
Nanoelectronics	nano* and device*, nano* and silic*, nano* and magnet*, nanowire*, quantum dot*, quantum wire*, molecular motor*, nanopowd*, nanophoton*, spintron*, nanostruc* (nano structured sensors), molecular*	1995	Chem	**67.85**	11.11	7.53	3.96	8.33	1.19	Less fusion with multi-disciplines
			Phy	3.84	**77.69**	8.46	0.38	7.3	2.3	
			Mat Sci	12.74	19.28	**53.26**	0.65	10.78	3.26	
			Biol	13.9	6.39	5.26	**61.65**	11.65	1.12	
		2000	Chem	**45.9**	17.27	18.29	2.95	7.3	4.37	
			Phy	10.99	**46.23**	13.94	3.12	12.86	6.87	
			Mat Sci	20.58	20.96	**39.89**	0.62	10.55	5.07	
			Biol	21.12	6.69	11.97	**41.9**	12.32	5.98	
		2005	Chem	**37.26**	14.47	20.37	10.18	10.72	6.97	Relatively high fusion with multi-disciplines
			Phy	14.48	**43.16**	19.39	7.1	9.01	6.8	
			Mat Sci	21.91	19.72	**33.69**	5.47	11.23	7.94	
			Biol	21.86	10.49	18.95	**34.11**	7.58	6.99	

Basis of Analysis — Selected top ranked journals in each discipline classified by Essential Science Indicators (ESI) and Journal Citation Report (JCR).
Search Method — Specific keywords derived from the Nano Science and Technology Institute (NSTI) publication.

nano-scale. Nano-dimension requires these different scientific fields by its own characteristics to understand each other and exploit nanotechnologies with new and much improved applications. By this way, it may develop some networks or linkages between disciplines and expertise, helping to boost with an efficient outcome in science. It appears from our investigation that nanoscience fusion across disciplines is a reality or started this trend just after having nano-instruments that opened a new door to explore unfocused area of various aspects of science. The basic strategy for fusion in Japan would be the researchers' keen intension to take advantages of using nano-tools or techniques in every disciplinary research, helped them to grasp new opportunities of nano-scale systems that could explore to address new realm of science of bridging separate disciplines[7]. The main factors of nanoscience fusion appear: curiosity drive to explore new things with new applications, scope of sharing or using nanoinstruments to observe nanostructures as well as to grasp funding since much funding is available in this prioritized area. We have also utilized descriptive statistics to explore the relevant factors of fusion in the case of Japan and provide our findings in the form of a spider graph, as illustrated in Fig. 7.

6.3. Similarity and disparity of fusion between Europe and Japan

For both cases of Europe and Japan, nanoscience fusion across scientific disciplines has appeared obvious from the findings. Nanoscience touches every spectrum of science in order to grasp scientific opportunities and its research output increases exponentially by disciplines as it explores a new way of conducting research in science, which can only spread by multi-disciplinary knowledge fusion. In the case of Europe, it has appeared a major feature of re-labelling research to pull funding from local and federal government as well as from EC, and attract funding from industry. Whereas in Japan this tendency has appeared in less to re-label rather than curiosity drive to explore new things through nanoscience. One of the reasons behind this would be availability of much funding to conduct research in this emerging field. The size of nanotech funding by Japanese government is almost the same as of EU, although the number of researcher varies significantly between two regions. Another disparity has appeared in our investigation is the existence of several inter-disciplinary research centers related to nanoscience both inside and outside of universities in European countries; however, this trend is appeared less in Japan. Nevertheless, government supported national nanotech infrastructures exist in Japan. What is a common of nanoscience fusion is the utilization of nano-instruments by scientific disciplines to explore new functions and applications of nanomaterials in both the regions.

6.4. Impact of Nanoscience Fusion

Nanoscience research system by its own characteristics pushes people from different background to get involved into it and therefore scientific disciplines are greatly affected. For example, the department of physics at University of Oxford has now included biological physics, while there was no biology within physics department few years ago. Due to nanotech research, physicists have an opportunity to culture biology, biological system, biological structures and biological functions. This example is strongly indicative of major changes within discipline. In addition, it was very unusual to find a strong collaboration between scientific departments at Oxford, but now they are culturing more inter-

[7] Interview with Professor Seizo Morita, Department of Quantum Electronic Device Engineering, Osaka University; interview with Professor Hiroshi Yokoyama, Nanotechnology Research Institute, AIST.

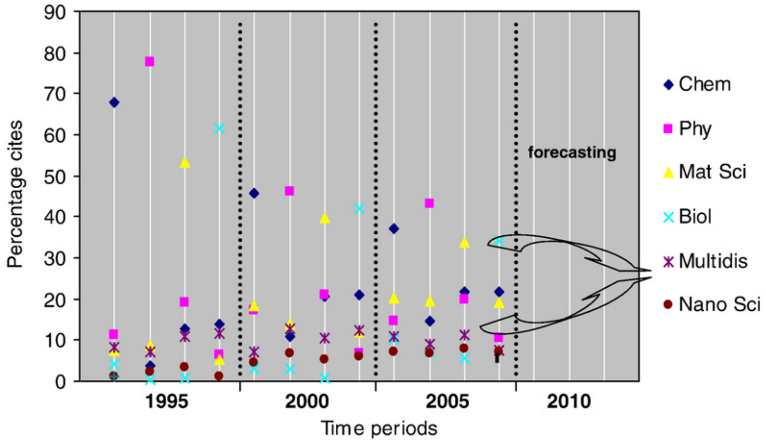

Fig. 5. Forecasting of nanoscience fusion in the electronics domain.

disciplinary programs that cause cultural changes within institutions. A few examples of impact by nanoscience fusion have identified. E.g.,

i) Researchers, who were doing simply chemistry or photochemistry, now have to move into photonics, physics of semiconductor, electrical engineering as well as optics due to nano-dimension (a case in Switzerland)
ii) A researcher whose affiliation was metallurgy working on nano-scale metallic materials and amorphous alloys since a long time ago, now focuses on simulations and modeling for semiconductors. Focusing areas also cover thin films, catalysis, hydrogen storage materials and especially supramolecular chemistry and biology (a case in Italy)

7. Developing a model of nanoscience fusion trajectories

Nanoscience and technology field is developing and spreading quite fast through different scientific disciplines and technology domains. Specially developing techniques or instruments for observing nano-scale is crucial. Nanoscience is inherently multi-disciplinary which transcend the conventional boundaries between scientific disciplines such as physics, chemistry, biology, material sciences. Therefore, we have developed an integrative framework to explore its fusion trajectory. It has identified in the previous sections that the

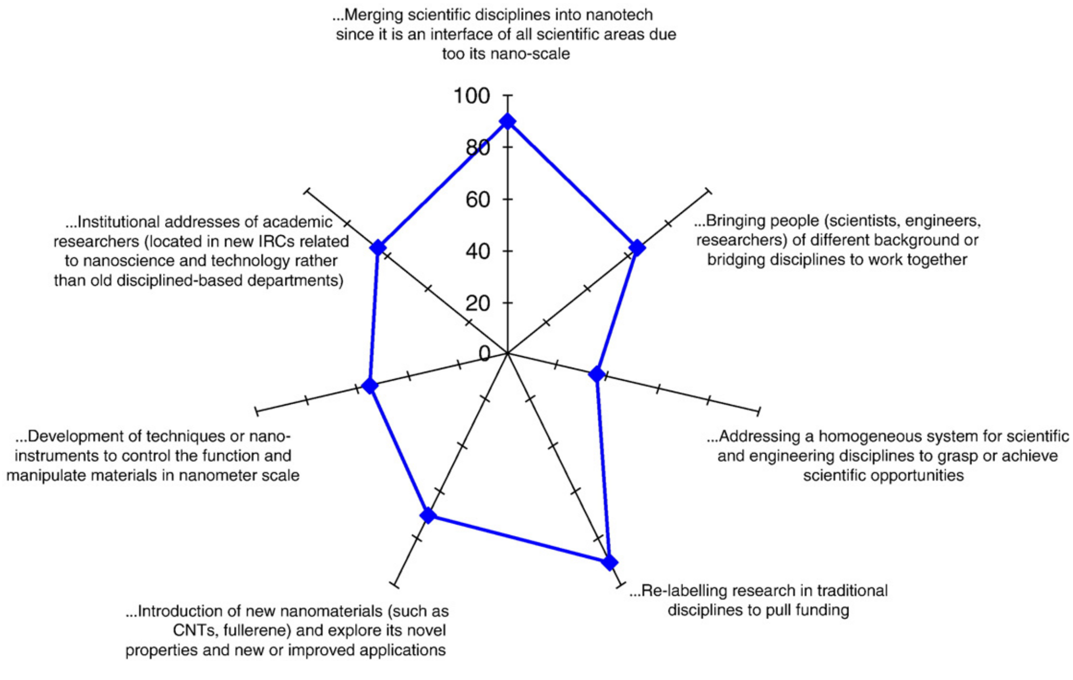

Fig. 6. Factors explaining nanoscience fusion in the case of Europe — percentage of interviewees believing this factor to have been important (relative distribution of answers given by nanotechnology academic scientists and researchers regarding nanoscience fusion trajectories).

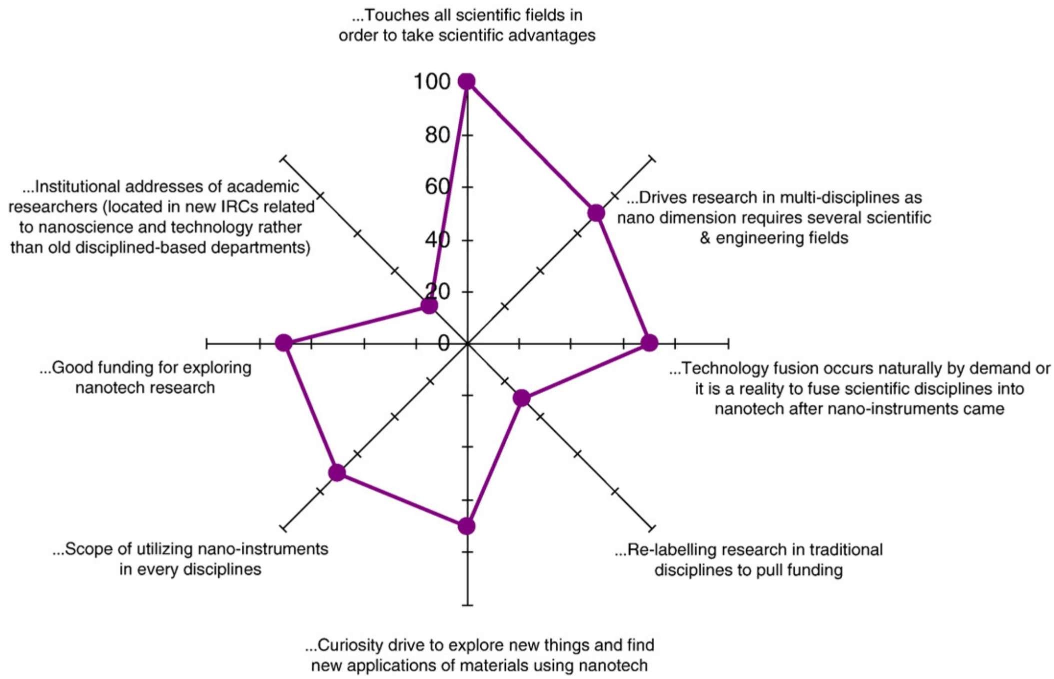

Fig. 7. Factors explaining nanoscience fusion in the case of Japan — percentage of interviewees believing this factor to have been important (relative distribution of answers given by nanotechnology academic scientists and researchers regarding nanoscience fusion trajectories).

basic scientific research trend has been changing from a separate disciplinary base to a type of more multi-disciplinary due to nano-dimension. Scientific disciplines were practiced separately at the very early stage of nanotech emergence. During 1990s when nano-instruments and nanomaterials came up with diversified functions and applications, scientific disciplines started to explore nanoscience and took advantages of increased funding as well as to re-label their research, as general disciplines were not getting much funding and

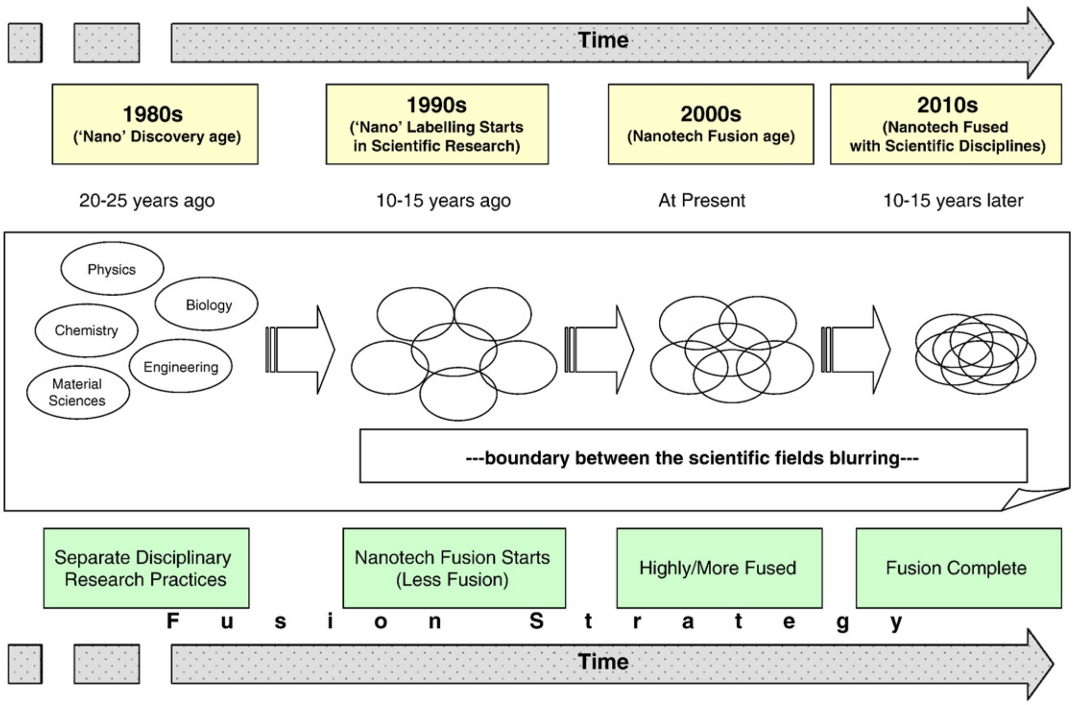

Fig. 8. Model of nanoscience fusion trajectories from its emerging phase.

thus tend to fuse within each other to share their expertise or joint work for nanotech evolution. At present (in the mid 2000s) nanotech research is highly fused through multi-disciplines since it seems almost impossible to do research in nanotech area without having strong connection of science and engineering disciplines.[8] Several examples were identified in the previous sections. After 10 to 15 years from now, it would be very hard to separate disciplines from multi-disciplines merging and the fusion would be complete due to societal demand of creating products with customized properties. Fig. 8 illustrates our predicted model of nanoscience fusion trajectories from its emerging phase.

8. Discussion and conclusion

Nowadays nanoscience and technology has been considered as an expansion area of the research fields in almost all scientific and technical disciplines at universities, public research institutes as well as in companies. The uniqueness of nanoscience lies not only on controlling and manipulating individual objects or nanostructures of matter in the atomic, bit and genomic level but also on providing new possibilities of manufacturing such as combination of bottom–up and top–down processes. Nano-scale research encompasses more distinct areas from materials and electronics areas to mainstream biomedical areas as diverse as gene therapy, drug delivery and novel drug discovery techniques. Therefore, nanotech research can be both mechanistic version (*more materials science and microelectronics inspired*, having new or significantly improved mechanical, electrical and chemical properties or functions) and bio-mimetic version (*more biotechnology inspired*, which requires the precise control of biological systems in order to achieve desired and designed outcomes). For developing nano-scale science and technology it is necessary to emphasize more multi-disciplines' dispersed research approaches.

In this paper, we tried to explore how nanoscience research is fused with traditional science fields such as chemistry, physics, material science and biology. The analyses addressed that chemistry, material science and physics have played an important role in fusing them rapidly accounting for a relatively higher share and significant growth in comparison with biological science which is instructive of the emerging field for nanotech. The paper has showed that the basic research trend of disciplines has been changing over time from highly separate disciplinary type to more type of multi-disciplinary. In the earlier phase, researchers linked with their respective disciplines' research, but now intended to share their expertise or knowledge to uptake more efficient outcome through nanoscience. This happens as a multi-disciplinary approach, trying to break down the boundaries of scientific disciplines. The discovery of new nanomaterials (e.g., carbon nanotubes, fullerene) and the development of techniques (e.g., nano-tools) to control and manipulate materials structure as well as self-assembly mechanism caused the fusion rapid. Finally, the finding has suggested an integrated framework of nanoscience fusion trajectories. The model, it has been argued, represents a real-time analysis on the exploration of fusion trajectories, and seeks to capture the attributes related to co-evolutionary nature of nanotech.

Promoting nanoscience fusion through scientific fields attracts much interest of policy makers because such pattern confirms the importance of collaborative research networks between divergent scientific fields as well as institutions in respect of nano-scale. The evidence in this paper indicated that nanoscience fusion trajectory contributes to innovation studies in a quite different way since such a fusion has understood rather a constellation of several distinct trajectories of scientific advance. Success in NanoSI thus requires scientists and practitioners to acknowledge new multi-disciplinary way of working. Therefore, it would be useful to adopt policy measures that could facilitate in building a network platform for sharing or exchanging different nano-expertise or knowledge by establishing and supporting nanotech IRCs and user facilities, designed to bring researchers from multiple disciplines together for the smooth functioning of NanoSI. This paper has made an original contribution to shed light on the process of measuring nanoscience fusion within NanoSI. Nevertheless, unlike other technology fusion, it explores a new way of doing SI for nanotech by muti-disciplinary fusion where people of different expertise work together and develop NanoSI. The concept of fusion through multi-disciplines proved useful to explain the dynamics of nanotech trajectory.

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