Paper to be presented at the DRUID 2011

on

INNOVATION, STRATEGY, and STRUCTURE -
Organizations, Institutions, Systems and Regions
at
Copenhagen Business School, Denmark, June 15-17, 2011

Contribution of Academic Entrepreneurship to Scientific Progress

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Abstract

In order to identify the effect of prevailing academic entrepreneurship on scientific progress, this paper compared the contributions of entrepreneurial scientists with those of conventional academics. In explaining the performance of differently typed scientists, we assumed that whereas search process of conventional academics is determined by the norm shared in the scientific community, the entrepreneurial scientists driven by non-conventional motivation would be partially liberated from the incentive system and play an important role in advancing the scientific frontier by giving birth to an unorthodox scientific agenda or hypothesis. In depending on the concept of "Pasteur's Quadrant", the results of statistical analysis applied to a sample of 1957 scientific papers published by 66 scientists confirm that although the overall research performance of "Pasteur scientists" (entrepreneurial scientists) are not as good as that of "Bohr scientists" (conventional academics), they make a greater contribution to furthering the scientific frontier by publishing more distinguished papers in terms of their impact on scientific community. The "Pasteur scientists," with their ability to work as boundary spanners between science and technology, not only accumulate expertise in finding industrial applications for scientific knowledge, but, obtain strong reputations for contributing to scientific progress in the field of advanced materials.

Jelcodes:O32,Z00

1. Introduction

Academic science has become increasingly entrepreneurial over the last decades as science and technology policies have reformed to strengthen the link between academia and industry (Etzkowitz 1983; Slaughter and Leslie 1997; Etzkowitz 1998). This policy direction toward academic entrepreneurship has brought about certain practical achievements such as university patenting and university start-ups. Many contributions in the literature have attempted to explain how the prevailing academic entrepreneurship influenced firmsôinnovation activity (Powell, Koput et al. 1996; Zucker and Darby 1996; Cohen, Nelson et al. 2002; Mowery, Sampat et al. 2002; Murray 2002; Zucker, Darby et al. 2002). Also, number of studies have examined the possible contribution of university-industry relations to productivity in science, mainly by investigating how scientistsôpatenting activities influence their publication performances in terms of both quantity and quality (Agrawal and Henderson 2002; Carayol and Matt 2004; Carayol and Matt 2006; Meyer 2006a; Meyer 2006b; Breschi, Lissoni et al. 2008; Fabrizio and Di Minin 2008).

In tandem with the research questions explained above, there has been a research tradition asking the nature of interaction between science and technology. In contrast to the common view emphasizing the causality as running from science to technology, a series of seminal papers explain that scientific knowledge of a wide generality sometimes grew out of a particular technical problem in a narrow societal context (Nelson 1962; Dosi 1982; Rosenberg 1982; Dosi 1988; Murmann 2003). From the viewpoint emphasizing the causality as running from technology to science, it can be assumed that university-industry relations would positively contribute to progress in scientific activities (Agrawal and Henderson 2002; Carayol and Matt 2004; Carayol and Matt 2006; Meyer 2006a; Meyer 2006b; Breschi, Lissoni et al. 2008; Fabrizio and Di Minin 2008).

However, does the interaction always work for the advancement of scientific frontier and overall progress of the scientific community? In order to identify the effect of prevailing academic entrepreneurship on scientific progress, this paper compared the contributions of entrepreneurial scientists with those of conventional academics. For the purpose of comparing academic contributions of differently typed scientists, we shed light on scientific papers published by each type of scientists, and compare differently grouped papers in terms of the averaged forward citation pattern, the impact on advancing scientific frontier (the share in the most frequently cited papers), and the speed of diffusion of the knowledge in scientific community. In explaining the performance of differently typed scientists, we assumed that search process of scientists would differ among each types, and, whereas search process of conventional academics is determined by the norm shared in the scientific community (Merton, 1973), the entrepreneurial scientists driven by non-conventional motivation would not necessary follow the norm. We believe their being partially liberated from the ordinary incentive system would play an important role in advancing the scientific frontier by giving a birth to an unorthodox scientific agenda or hypothesis in the scientific community.

In operating our inquiry, we opted for depending on the concept of ñPasteurôs Quadrantò (Stokes 1997). As for the typology of scientists, Stokes proposed a classification of scientists based on their inclination towards science and technology. Three types of scientists are identified: ñEdison scientistsò, ñBohr scientistsò and the ñPasteur scientists.ò The first conduct pure applied research, oriented to bring about knowledge for real-world utility, having no interest in deepening understanding of basic science; the second conduct pure basic research, oriented to the pursuit of knowledge for its own sake through scientific discovery, having little interest in the potential uses of their research findings for the real world; the third also conduct basic research, never lose sight of the hope to advance scientific understanding for their contributing to real-world utility.

In referring to the case of Pasteur as a scientist, although solving practical fermentation problems derived from his relationship with French distilling industry, Pasteurôs interest in the phenomenon is also led by the ñpreconceived (scientific) ideasò, which enabled him to become the founder of bacteriology (Geison 1995:95). Setting the type of ñPasteur scientistsò as an independent category seems relevant because of the following reasons: viewed from the theory of technical change, drawing ñthe line on the basis of the motives of the person performing the research ï whether there is a concern with acquiring useful information (applied) as opposed to a purely disinterested search for new knowledge (basic)ò is irrelevant since some of the most fundamental scientific breakthroughs have come from people, who thought they were doing applied research (Rosenberg 1982:149) and; viewed from the sociology of science, it is known that heterogeneity of scientistsômotivation is more complex than the dichotomy of ñprofessionalò rewards in scientific community and private financial gain (Merton, 1973), which includes the motives such as intellectual challenge as well as contributing to the society (Sauerman, Cohen et al. 2010). Traditionally, the number of patents is taken as a degree of scientistsômotivation for pursuing commercial activities, but financial returns are not the key reason for the scientists active in bio-medical sciences, to get involved in patenting.

For the purpose of clarifying the impact of prevailing academic entrepreneurship, we know the fact that modern science has become an integral part of the political system (Blume 1974), denying the traditional assumption of the autonomy in the scientific community (Merton 1973) and structure of scientific norms is determined by context such as scientific fields, historical periods, and organizational environments (Hackett 1990; Frickel and Moore 2005). In this paper, we chose to focus on the scientific activities in Japan where the emerging entrepreneurial institutions modeled after the US system make it easier for the universities and their faculty to engage more directly in commercial activity (Walsh, Baba et al. 2008). The reforms have led a great number of scientists to be involved in entrepreneurial activities since the mid-1990s, which is implied by the increasing number of patent applications from universities, university-industry relationships, university startups, and technology transfers (Nagaoka, Kondo et al. 2009: 186).

Regarding the focal scientific field, we chose the activities in the field of advanced materials, particularly, in the narrow technological field of the TiO_2 photocatalyst. The choice of scientific field derives from the fact the interaction between science and technology is particularly relevant in the field of advanced materials, because it leads, on the one hand, to the generation of new scientific knowledge, and, on the other, to the identification of industrial applications for scientific discoveries (Niosi 1993; Schmoch 1997; Maine and Garnsey 2006). Also, we chose to focus on the sub-field of the TiO_2 photocatalyst in that emerging academic entrepreneurship in the field has greatly contributed to the utility of society by opening up a wide range of industrial applications to bring about sizable markets all over the world (Baba, Yarime et al. 2010). The following analysis is mainly based on the bibliographic data taken from the database Scopus (Elsevier 2010) and patent data taken from the Japanese patent database (IPDL), but, we managed intensive interviews in the mid 2000s on the ñ Pasteur scientistsò in the field based on the semi-structured questioners.

Armed with our sample of scientific papers published by all the Japanese scientists involved in the research, we statistically compared the scientific performance of entrepreneurial scientists with that of conventional academics and identified the impact of academic entrepreneurship on the contribution to scientific progress. The results of quantitative analysis applied to a sample of 1957 scientific papers published by 66 scientists confirm that although the overall research performance of ñPasteur scientistsò are not as good as that of ñBohr scientists", they make a greater contribution to furthering the scientific frontier by publishing more distinguished papers in terms of their impact on scientific community. The ñPasteur scientists,ò with their ability to work as boundary spanners between science and technology, not only accumulate expertise in finding industrial applications for scientific knowledge (Baba, Shichijo et al. 2009), but, obtain strong reputations for contributing to scientific progress in the field of advanced materials. Based on the findings, this paper provides suggestions, firstly with science policy makers on how to prioritize funding and resources toward scientists when universities and public research organizations face increasing budget reduction, and secondly with scientists or university administrators on how to build research policy for tiding over tightening competition in scientific community.

The paper is organized as follows. Section 2 reviews the previous research on the issue, providing an analytical framework to investigate the nature and functions of entrepreneurial scientists or ñPasteur Scientistsò and presents our testable hypotheses. Section 3 introduces the case study of ñPasteur Scientistsò in the photocatalyst research in Japan and describes the data and methodology. Section 4 presents the results of quantitative analyses. Finally, section 5 provides concluding remarks, some policy discussions, and the limitations of the research.

2. Theoretical background and hypotheses

In solving scientific problems, scientists are known to use several types of logic and reasoning (Peirce 1932; Dewey 1938; Sebeok and Umiker-Sebeok 1980; Rao 1997). The conventional model of academics is ñBohr scientistsò, who set the goal of producing codified theories and models that explain and predict natural reality and embark on a course of research that involves stipulating preconditions by simplification and reduction of the number of observable variables. The essential skills of the conventional academics are known ñto simplify the essential to allow modeling and predictionò (Pavitt 1998:795). Those scientists usually use logical types of deduction (verification of proposed theories) and induction (creation of new knowledge based on observational data) for solving problems within an established scientific discipline (Kuhn 1970)[1].

There is another type of logic and reasoning, abductive reasoning, originally advocated by C.S. Peirce, a nineteenth-century pragmatic philosopher (Peirce 1932), is the cognitive process of articulating a hypothesis that provides a consistent explanation of the various observed data and phenomena (Sebeok and Umiker-Sebeok 1980). In solving problems, technological developers (including the type of ñEdison scientistsò) are known to use abductive reasoning, i.e. creation of new knowledge by intuition without data (Rao 1997)[2] largely based on synthetic knowledge base (Baba and Nobeoka 1998; Takeda, Yoshioka et al. 2001). Taking an example of Edison, although he is notorious for his weakness in mathematics, Edison

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1 We admit that conventional academics sometimes use abductive reasoning for branching out a new scientific paradigm. Regarding the modes of search process used by great physicists, although majority falls in "Yukawa (Bohr) mode" i.e. using induction and deduction deeply rooted in experimental data, very few falls in "Dirac Mode" using abduction i.e. the wild, speculative leap in mathematical logic that led to astonishing discoveries, like Dirac's theory of antimatter and Einstein's theory of general relativity (Comment of Nambu (Nobel Prize winner 2009) in 1985 (Kaku and Thompson 1987:85))

2 The distinction between induction and abduction is somewhat subtle (Rao,1997) In induction, scientists are guided by experimental data and its analysis to provide an insight. But the ultimate step in the creation of new knowledge does depend on previous experience and a flight of imagination

has ñtalent for asking questions that could be translated into hypothesis, which in turn established the strategy and tactics of experimentationò(Hughes 1983:26).[3]

Following the definition of ñPasteur scientistsò, we assume that scientists under this category would entail faces of both ñBohrò and ñEdisonò scientists. The ñPasteur scientistsò, having two faces allow them to use either deductive/inductive or abductive reasoning depending on the type of problem solving on suite: the face of ñBohr scientistsò uses deductive/inductive reasoning for deepening the understanding of science; the face of ñEdison scientistsò uses abductive reasoning for developing useï inspired technologies. Partially borrowing from ñEdison scientistsò, ñPasteur scientistsò set the goal of arriving at an understanding of how the phenomenon behaves under a given set of conditions and embark on a course of research that explores the technological possibilities for satisfying user needs in a society. The research processes are ñoften complex, involving numerous components, materials, performance constraints and interactions, and are therefore analytically difficult to handle.ò and the essential skills of ñPasteur scientistsò are ñto integrate the essential to ensure target performanceò and ñto identify performance limits.ò (Pavitt 1998:795). Armed with the two faces, ñmany able scientists, of whom Pasteur is a fine example, have found no conflict in focusing on particular fundamental problems because of their practical utilityò (Metcalfe 2010).

Next, looking at the tradition of sociology of science, we know that scientistsô incentive for conducting research is to obtain appraisal from their peers in the scientific community and improve their standing within scientific community (Merton 1973). In the sort of social norm, each scientist is known to feel an essential tension between tradition and originality (Kuhn 1977). They must be traditional

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3 When Edison began his research on the incandescent light bulb, the technology already existed for lighting up a filament inside a glass bulb by conducting an electric current into it. However, the filaments that existed at the time would burn out in two hours, making it difficult to market them as replacements for gas lamps. Scientists at the time took it for granted that filaments would burn out (oxidize) quickly at temperatures high enough to give off light, so they did not work on ways to extend the life of incandescent bulbs. Edison, on the other hand, did not have the scientific understanding that it was physically difficult to create the phenomenon of illumination while simultaneously prolonging that phenomenon. As a result, he carried out a process of trial and error, using 7,000 different types of materials before he succeeded, by chance, in extending the life of his incandescent bulbs to 300 hours.

enough to establish strategic similarities that connect their work to that of others in the field, yet original enough to establish strategic differences that impart novelty to their work (Hackett, Conz et al. 2004; Hackett 2005). Thus we assume that the search process employed by conventional academics could be constrained by the scientistsô single-minded incentive to present their research results to the peers in scientific community in a form that can be properly evaluated and preferably cited.[4] From this perspective, those scientists adopt research agendas and experimental protocols that do not differ considerably from those used in earlier research in the field, and they opt for using deductive/inductive reasoning to carry out their analyses.

The reasoning for the claim is that, in the first place, if scientists show strategic similarities while managing to show a certain degree of originality, they can produce the type of papers that they can expect to have a reasonably good adoption rate. Second, since deductive/inductive reasoning, if conducted according to the proper procedures, are essentially infallible analytical methods (Rao 1997), if scientists fully depend on the methodology, they can reduce the unavoidable risks associated with the process of scientific problem solving . Third, by publishing papers in pre-existing research fields, scientists can expect their papers to be cited by researchers already contributing to that field. As a result, based on the research strategy, they can ensure a number of citation counts of their published papers.

Entrepreneurial scientists, on the other hand, pay attention to their socio-industrial profile as well as their profile in the scientific community, and maintaining these two profiles gives their search process the following characteristics. First, in addition to their incentive to publish papers for the scientific community, entrepreneurial scientists can be seen to have another type of motivation for advancing their research. That motivation grows out of their commitment to making a social contribution through university-industry relations, or participating in publicly supported programs.

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[4] We admit that citations are not the same as evaluations in that (i) a paper may be evaluated many times by people who read it and yet do not cite it and (ii) the criteria of citing a paper is not homogeneous: some papers could be cited as examples of counter-arguments. Having noticed these limitations, we use the citation as a proxy of evaluation in the science community since we do not have any evaluation index on the quality of papers other than citations.

Clearly, the entrepreneurial scientistsô emphases on living up to the social commitments make them less interested in the essential tension between tradition and originality that the conventional academics usually feel. The fact means when the type of scientists designs their search process, they are liberatedð even if only partially soð from the incentive to present their research findings in a format that their peers in the scientific community may positively evaluate. Research orientation differs among three types of scientists in the ñPasteurôs Quadrantò, affecting the nature, direction, and pace of their scientific performance. And the observation above leads to the following hypothesis as to the scientists that are more entrenched in the scientific community, that is, ñBohrò and ñPasteurò scientists:

Hypothesis 1: When we compare the averaged research performance of ñPasteur scientistsò with that of ñBohr scientistsò, whereas the papers published by the latter entail a good performance (much of their papers are frequently cited, and few of them are marginally cited), the papers published by the former entail a relatively poorer performance (the proportion of frequently cited papers is lower, and the proportion of marginally cited papers is higher than those published by the latter).

When pre-existing research agendas and experimental protocols make it difficult to achieve R&D objectives they have established in accord with their social commitments, ñPasteur scientistsò develop a hypothesis and advance their research through unorthodox research agenda and experimental protocol left behind in the march of previous scientific progress. At the same time, they anticipate the possible risks of their hypothesis being fallible since they proceed to create knowledge by intuition without relaying the supporting data. When this happens, although the winning percentage is only slim, the ñPasteur scientistsò are bestowed with an opportunity to ensure target industrial performance and break through an existing scientific frontier. And the observation above leads to the following hypothesis:

Hypothesis 2: The chance of ñPasteur scientistsò to make a contribution to the scientific breakthrough is higher than that of ñBohr scientistsò. Given the wining percentage is similar between the two parties, the ñPasteur scientistsò show higher propensity on break through the scientific frontier by publishing more distinguished papers than do ñBohr scientistsò.

To recapitulate, reflecting their research orientation in the scientific community, ñPasteur scientistsò pay less attention to attract interest of their peers for increasing the number of citation counts than do ñBohr scientists.ò Also, in the industrial setting of advanced materials, ñPasteur scientistsò do not carry out their research based on a single scientific discipline alone; they continue search process, occasionally with a new protocol based on multiple theories crossing over several scientific disciplines. Their research orientation takes the risk of stagnating citation counts of their papers, since the community of scientists who are willing to cite their papers is relatively limited at the time of their publishing papers. As understanding on the nature of the research diffuses in the scientific community, the size of the citing community gradually grows afterwards. And the observation above leads to the following hypothesis:

Hypothesis 3: It takes longer for the ñPasteur scientistsò to get their papers cited than do for the ñBohr scientistsò since scientific contents produced by the former diffuse more slowly in the scientific community.

3. Empirics

3.1 The Case of “Pasteur scientists” in the field of advanced materials

Judging from our standpoint, it is rather difficult to analyze the impact of academic entrepreneurship on scientific performance without taking the view that the nature of research varies substantially among scientific fields. In terms of knowledge base used, there are two types of industries depending on the ñanalyticalò or on the ñsyntheticò(Asheim and Coenen 2005; Moodysson, Coenen et al. 2008). The field of advanced materials is explained as a setting comprising of analytical and synthetic knowledge base and the innovation process in the sector is relevant with a two-way interaction between scientific knowledge (know-what) and engineering knowledge (know-how) (Baba, Shichijo et al. 2009).

Among the various types of advanced materials, photocatalyst is considered to be industrially promising because they activate novel functions using only sunlight. When TiO_2 absorbs ultraviolet light, the TiO_2 photocatalyst demonstrates a very strong oxidation power that decomposes most organic compounds adsorbed on substrate. Such catalytic reactions induced by light are called photocatalysis (Fujishima, Rao et al. 2000). These findings on the novel functions have opened up a wide range of industrial applications and brought about a series of product developments. PIAJ (Photocatalysis Industry Association of Japan) estimated the size of the worldwide commercial photocatalyst market as 1,000 million US dollars in 2009.[5]

For illustrating the influence of ñPasteur scientistsò on scientific progress, this section focuses on the activity of Kazuhito Hashimoto at the University of Tokyo, who made scientific breakthroughs, published scientific papers extensively and acquired numerous patents including those of fundamental importance. When utilizing TiO_2 photocatalyst for industry, combining science with user needs becomes indispensable. This is achieved, in university-industry relations, through close interactions between the scientists, who create a model for materials design and supply the proof of concept, and the industry, which understands the needs that the end user brings to the product.

When considering how photocatalyst could be used for industrial applications, Hashimoto first hit upon deductive reasoning. When a material coated with TiO_2 photocatalyst is exposed to natural light, the number of photons in ultraviolet light sets the performance limit. If the photocatalyst is dispersed throughout a three-dimensional space like liquid, industrial applications would be difficult because of insufficiency of photons as energy source. In order to determine the material

[5] The first product design utilizing oxidation power makes it possible to develop anti-bacterial ceramic tiles and so forth; the second design, utilizing super-hydrophilicity, develops self-cleaning building materials and anti-fogging window glasses, leading to the creation of new markets.

design for industrial application, abductive reasoning plays an important role: Hashimoto produced the hypothesis that if photocatalyst was to demonstrate marketable functions, they had to be applied to two-dimensional surface. When this reasoning was formulated, it resulted in the university-industry relations with a sanitary manufacturer TOTO, which started to coat tiles and other building materials with TiO_2 photocatalyst. Having gone through research with a new research protocol, Hashimoto soon discovered that solid surfaces coated with TiO_2 photocatalyst show decomposition effects with active oxygen on the surfaces. For the purpose of understanding the mechanism of the effect, the ñPasteur scientistsò speculated through deductive/inductive reasoning on the effect and submitted a paper to the top science journal. Also, university and industry jointly applied for patents for the function, and TOTO developed the worldôs first anti-bacterial tiles in 1994.

Together with the direct contributions that university-industry relations add to the scaling up of the universitiesôresearch activities, the case suggests that the university-industry relations enable the ñPasteur scientistsò to extend their search activities further into unexplored research areas. For instance, in 1995, TOTO researchers collaborating with the university discovered super-hydrophilicity, a novel function of photocatalyst, in a serendipitous manner. As a long-term research partner, Hashimoto took part in the scientific aspects of the joint research, including detailed investigations into the mechanisms behind phenomena in the discipline of surface sciences. Their joint paper with TOTO published in *Nature* in 1997 (Wang, Hashimoto et al. 1997) obtained numerous citation counts. Also, university and industry jointly applied for patents for a much wider range of industrial applications, and TOTO developed self-cleaning tiles in the following year.

3.2 Methodological notes

Evaluating research activities of individual scientist is far from easy, since in the scientific fields where experiment works crucially for problem solving, scientific inquiry is carried out collectively, led by the head of the laboratory, who happens to be either professor or principal investigator of funded project. In this paper, we aim at focusing on the activities of these leading scientists, who have full responsibility on research at laboratories by initially setting research agenda and experimental protocol. Although previous research uses individual researcher or professor (Breschi and Lissoni, et. al, (2008) and many other article) as a unit of analysis, adopting the unit is bound to include the performance of co-authors collaborating with the leading scientists. Those co-authors are often members of a laboratory headed by a leading scientist, who can be graduate students, post-docs and so on.

For the purpose of sorting out those subordinate co-authors to identify the sample of leading scientists in the field, we collected the record of all the individual authors of the sample papers and compared their publication patterns. If a certain authorǒs research portfolio (i.e. a set of publications) is broadly similar with other authors, we selected the scientist with the top research portfolio and assumed he/she as a leading scientist. By using the method of filtering junior co-authors, we obtained a sample of leading scientists, i.e. the laboratory heads in universities or public research organizations (PROs), which we considered our unit of analysis. [6]

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[6] By way of using the research portfolio of those researchers, we tried to sort out what we called leading scientists. The filtering process is as follows: 1) authors of papers are sorted according to the number of articles. Comparison of publication patterns is done from the author with the largest to the one with the smallest number of articles; 2) first scientist (the author with the largest number of articles) is treated as a leading scientist; 3) portofolio vector of scientists is defined as $v_c \equiv (p_{1,c}, p_{2,c}, \ldots, p_{n,c})$ where $p_{i,c} = 1$ if scientist c is included as author of article i, otherwise 0. 4) To evaluate the similarity of portfolio, we calculate Salton's cosine similarity measure Salton, G. and M. J. McGill (1983). Introduction to modern information retrieval. Auckland, New Zealand, McGraw-Hill. of candidate's portfolio vector v_c and each leading scientist's portfolio vector v_l defined as $\frac{v_c \cdot v_l}{|v_c| \cdot |v_l|}$. If the similarity measure is larger than 0.5, we assumed that candidate's portfolio is too similar to that of leading scientist, hence the candidate is canceled as junior authors. This threshold value (0.5) is arbitrary although the result does not change much (less than 5%) if we change threshold to 0.3 – 0.7.

3.3 Data and sampling procedure

For the purpose of classifying the ñPasteurôs Quadrantò, we apply the following rules: for measuring a scientistôs inclination to deepen scientific understanding, we use the number of his/ her citation counts divided by the number of his/her publications; for measuring a scientistôs inclination to contribute to social utility, we use the number of patent applications.

Publication data

To evaluate the performance of scientists involved in photocatalyst research, we searched scientific papers related to the keyword ñphotocatalystò using bibliographic database Scopus (Elsevier 2010).[7] As a result we obtained 15,219 articles published from 1960 to 2010 from worldwide. Since our present observation is focused on the papers with authors who are affiliated to the Japanese universities or PROs, our sample comprises of 3,832 articles. For those articles, first, the name of an individual author is identified. A pairing data of author and affiliation is used to distinguish an individual researcher; if two authors shared the same name, the data on affiliation informs if they are the same person or not. To achieve this task, we used the data sources including national researcher database (JST 2010), JSPS funding database (NII 2005-2010), as well as personal and organizational web pages. As a result, we identified 3,537 individual scientists, spanning 127 academic organizations. Next, we excluded a body of junior co-authors by using the publication-similarity based filtering[8]. After all, we identified 66 leading scientists, namely, 52 belonging to universities, and 14 belonging to public research organizations.

Patent data

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7 Here the search expression TITLE-ABS-KEY(photocatal*) is used to extract article whose title or abstract or keywords matches with "photocatal*". Since the asterisk means wildcard, this expression matches with photocatalyst, photocatalysis, photocatalyic and so on.

8 By comparing research portfolio, 3032 candidates' portfolio is found to be fully included by certain independent researcher. The remaining 505 candidates are further examined and 439 candidates are dropped due to similarity criterion.

To evaluate the degree of entrepreneurial activities of scientists, we obtained all the patents applied by the sample scientists to Japan Patent Office (JPO) in the field of Photocatalysis in the period 1970-2008. For the patents, we counted the number of patents applied by each leading scientists as an inventor.[9]

Identification of the "Pasteur's Quadrant"

We clarify which 66 leading scientists belong to each category in the ñquadrant model of scientific researchò (Stokes 1997) according to two measures: the number of patent applications (PAT) and the average scientific contributions (ACITE), which is built dividing the number of his/her citation counts by the number of his/her publications. We propose a classification of 66 leading scientists into four quadrants: for measuring a scientistôs inclination to deepen scientific understanding, we use the number of his/ her citation counts divided by the number of his/her publications (vertical axis); for measuring a scientistôs inclination to contribute to social utility, we use the number of patent applications (horizontal axis). We take as a reference line the average value of each variable. **Table 1** illustrates the attributes of each scientist category in terms of (i) average number of scientific papers published per-researcher, (ii) average sum of citations counts per-researcher, and (iii) number of researchers belonging to the category.

[9] Since the result of this search method includes type I errors (i.e. including patents of a different inventor sharing the same name), spurious patents were removed, after examining the address of each patent inventors.

Table 1 Classification of scientists

Average of citations (ACITE)		Number of patents (PAT) Less <15.36	Number of patents (PAT) More Ć15.36	Total
	More <23.94	*Bohr scientists*	*Pasteur scientists*	
		33.2 papers	76.7 papers	51.6 papers
		1219.6 citations	2844.6 citations	1907.1 citations
		15 (3) researchers	11 (6) researchers	26 (9) researchers
	Less Ó23.94	*Others*	*Edison scientists*	
		21.1 papers	41.0 papers	24.6 papers
		341 citations	801.7 citations	421.6 citations
		33 (3) researchers	7 (2) researchers	40 (5) researchers
Total		24.9 papers	62.8 papers	35.2 papers
		615.6 citations	2050.1 citations	1006.8 citations
		48 (6) researchers	18 (8) researchers	66 (14) researchers

Note: Figures in parenthesis are number of researchers who belong to PROs.

4. Empirical Results

4.1 Comparing the patterns of publication impact

In order to identify the averaged patterns of forward citation for each type of scientists, we focused on the sample 1957 articles authored by 66 leading scientists. First, we classified the sample articles into four classes according to the number of forward citations they received: those are classes of large citation counts (top 25% articles in citation counts ranking), medium large citation counts (top 25% to 50% articles), medium small citation counts (top 50% to 75% articles), and small citation counts (bottom 25% articles). Second, we re-classified the articles in each class into four categories: those articles that include at least one ñPasteur scientistò as author, and the same for the ñBohrò and ñEdisonò scientists, and others The 210 articles have more than two types of leading scientists as authors, thus the result of this classification is not-strictly disjoint, however, the effect of this overwrap is possibly small. The result derived from the classification is shown in **Table 2**

Next, we calculated the share of each scientist-type in the 4 citation counts classes. of As for the large citation counts class, we found that the share of ñBohr scientistsò is 39%, the one of ñPasteur scientistsò is 29%, and the one of ñEdison scientistò is

22%, respectively. Also, as for the class of small citation counts, we found that the share of ñBohr scientistsò is 12%, the one of ñPasteur scientistsò is 20%, and the one of ñEdison scientistsò is 22%. Looking at the averaged patterns of forward citations of each scientist-type (see, Figure 1.), it can be suggested that the pattern of ñBohr scientistsò is more favorable than those of ñPasteurò and ñEdisonò scientists viewed from the traditional research evaluation, that is, more papers published by ñBohr scientistsò are frequently cited and fewer papers fail to be properly cited. In stark contrast, relatively fewer papers published by ñPasteur scientistsò are frequently cited and more papers published by ñPasteur scientistsò are marginally cited.

Furthermore, in order to compare the performance of Bohr scientists and Pasteur scientists statistically, we evaluated rank distribution of articles authored by scientists belonging to each type. To do this, we calculated rank to each article, and distribution of this rank value among different scientists type are compared. The histogram of rank-distribution is shown in Figure 2. As the figure shows, for Bohr scientist, larger share of articles are highly ranked and lesser share of articles are ranked low. By contrast, for Pasteur scientist, the share of articles by citation rank is distributed rather homogeneous. The mean of citation rank of Bohr scientists is 868.4(standard error of the mean is 30.97), which is significantly smaller (P=0.0011) than that of Pasteur (997.8, standard error of the mean is 22.83). Thus we can suggest that the pattern of ñBohr scientistsò is more favorable than those of ñPasteurò and ñEdisonò scientists from the viewpoint of research evaluation, that is, more papers published by ñBohr scientistsò are frequently cited and fewer papers fail to be properly cited. In stark contrast, relatively fewer papers published by ñPasteur scientistsò are frequently cited and more papers published by ñPasteur scientistsò fail to be properly cited.

Table 2 Distribution of publication impacts of each type scientists

	Pasteur	Bohr	Edison	Other
Large impact	225 (29%)	179 (39%)	61 (22%)	110 (16%)
Medium large impact	196 (25%)	128 (28%)	71 (25%)	170 (25%)
Medium small impact	200 (26%)	97 (21%)	88 (31%)	221 (33%)
Small impact	157 (20%)	54 (12%)	63 (22%)	168 (25%)
Total articles	778	458	283	669

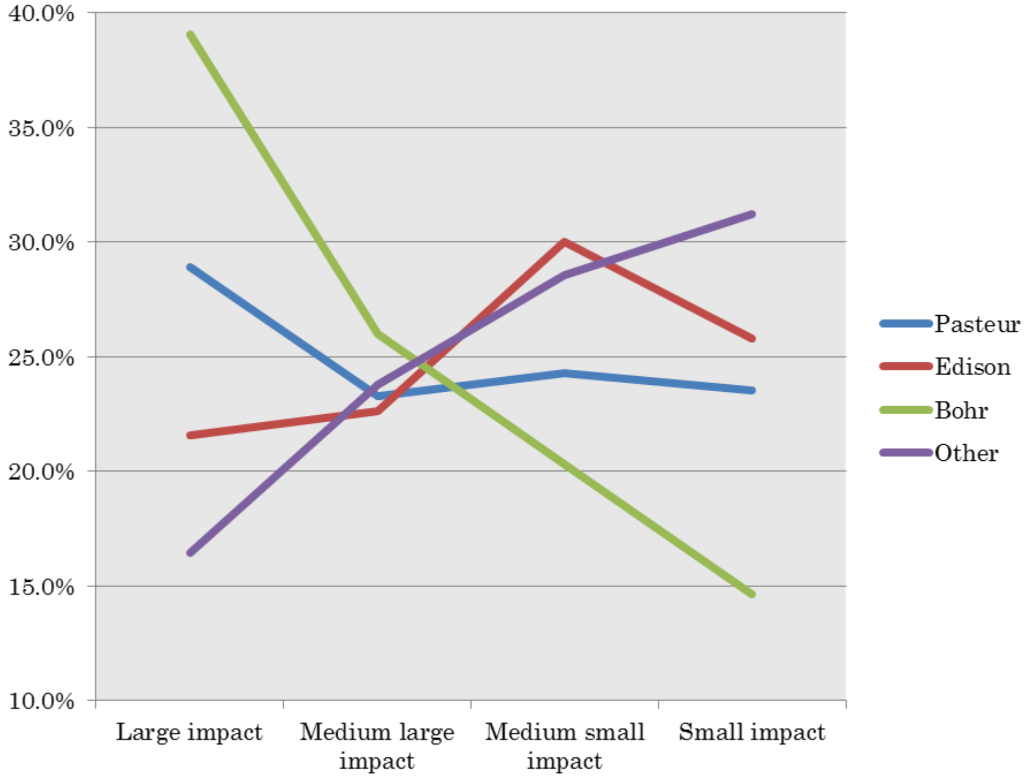

Figure 1 **Comparison of publication impact breakdown**

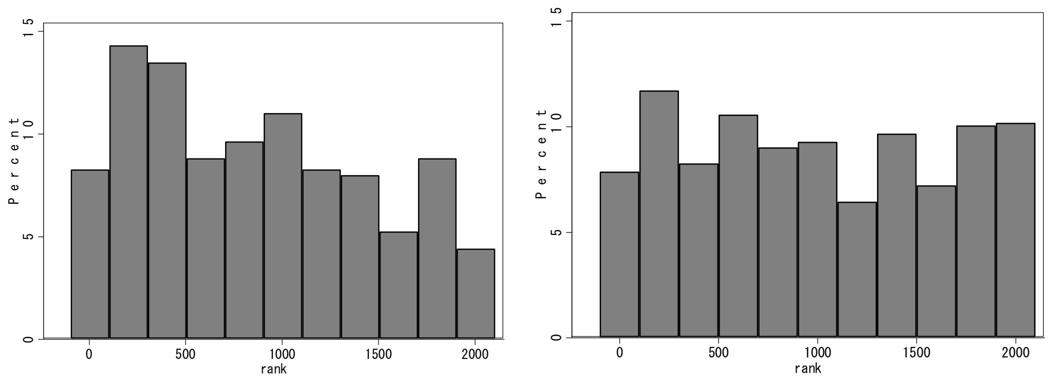

Figure 2 Distribution of article citation rank

4.2. Comparing impact on advancing scientific frontier

In order to compare the impact on advancing scientific frontier of each scientist-types, we collected the top 100 papers out of the sample articles authored by 66 leading scientists in terms of the number of their citation counts. Also, we selected the top 0.5% articles (20 articles) and the top 1.0% (40 articles). Next, we classified the papers in each class into those authored by the four types of scientists and compared the share of each type in those classes respectively. As shown in Figure 3, for the highest ranked distinguished papers (the top 0.5% articles), the share of papers authored by ñPasteur scientistò is significantly larger (around 70 %) than those authored by any other type of scientists. Even extending our observation to the highly ranked papers (the top 1% articles), we can see the similar tendency. In contrast, the share of papers authored by ñBohr scientistsò is smaller (around 20%) in both of the highest and higher classes. Our finding suggests that ñPasteur scientistsò, no other than ñBohr scientistsò make a greater contribution to furthering scientific frontier.

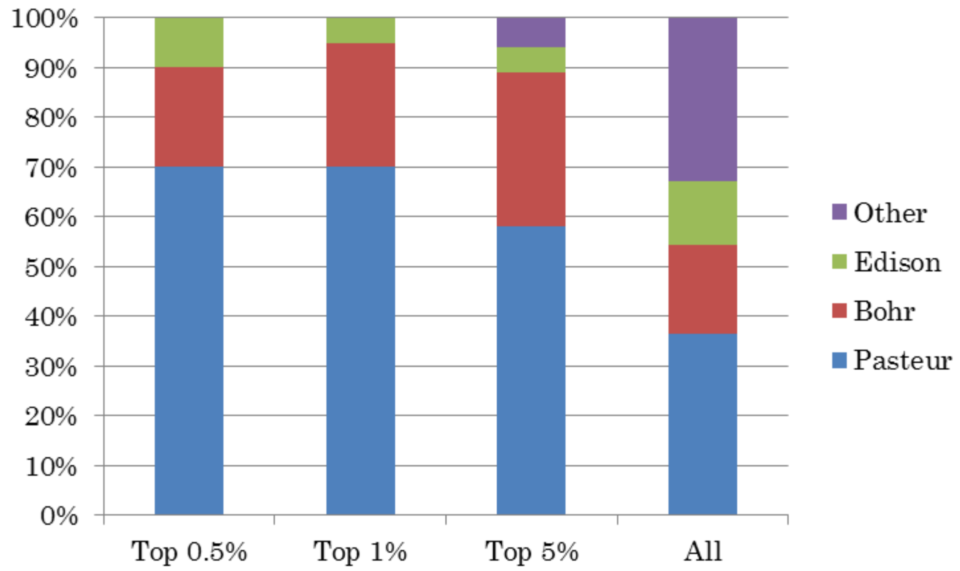

Figure 3 Share of scientists in the highest/highly ranked articles

Next, let us test our hypothesis 2 by selecting individual articles as a unit of analysis. A set of Poisson regression models were estimated to evaluate how the type of authorship influences the scientific quality of the articles in terms of the cumulative number of forward citation counts.

Table 3 describes the variables at the article level of analysis. Since the amount of labor injection may affect the quality of outcome, the number of co-authors is included as control parameter. Similarly, if the researcher continued their research for longer years, the more knowledge may accumulated, hence affects the quality of outcome. It needs some notice in interpreting 4-dummy variables because they are not mutually exclusive. Since a large number of papers are co-authored by different type of scientists, those papers are classified, for example, both as PASTEUR and EDISON.

Table 4 shows the descriptive statistics, **Table 5** shows the correlation matrix. The result of estimation is shown in **Table 6**. In **Table 6**, model (1) estimates the overall effects of authorship on impact, while model (2) focuses on the large impact articles (top 25%), accordingly, model (3) (4) (5) estimate the effect for medium large impact, medium small impact, small impact articles respectively.

The results of the Poisson regressions estimation suggests that articles (co)-authored by the ñPasteurò or ñBohr scientistsò are more likely to receive many forward citation, compared to articles (co)-authored by the ñEdison scientistsò or others. However, when we focus the analysis on the top 25% articles, the article (co)-authored by the ñPasteur scientistsò is of better quality, while (co)-authorship with ñBohr scientistsò has no significant effect on quality. This result supports Hypothesis 2.

Table 3 Variables description (Article level)

Type	Name	Description	Source
Dependent variable	CITE	Number of cumulative forward citations.	Scopus
Independent variables	PASTEUR	Dummy variable (1/0) denoting if the paper is authored by a Pasteur scientist.	Scopus/IPDL
	EDISON	Dummy variable (1/0) denoting if the paper is authored by an Edison scientist.	Scopus/IPDL
	BOHR	Dummy variable (1/0) denoting if the paper is authored by a Bohr scientist.	Scopus/IPDL
	OTHERS	Dummy variable (1/0) denoting if the paper is authored by Others.	Scopus/IPDL
Control variables	AUTH	Number of authors of the paper.	Scopus
	AGE	Age of the article (i.e. number of years passed after publication).	Scopus
	UI	Dummy variable (1/0) denoting if the paper is co-authored by a corporate researcher.	Scopus

Table 4 Descriptive statistics (Article level)

Variable	Obs	Mean	Std. Dev.	Min	Max
CITE	1957	26.67	59.23	0	1878
PASTEUR	1957	0.40	0.49	0	1
EDISON	1957	0.14	0.35	0	1
BOHR	1957	0.23	0.42	0	1
OTHERS	1957	0.34	0.47	0	1
AUTH	1957	3.19	1.70	1	12
AGE	1957	8.72	6.14	0	34
UI	1957	0.08	0.26	0	1

Table 5 Correlation matrix (Article level)

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)	CITE	1						
(2)	PASTEUR	0.0775***	1					
(3)	EDISON	-0.0335	-0.2495***	1				
(4)	BOHR	0.0689**	-0.1517***	-0.0764***	1			
(5)	OTHERS	-0.0891***	-0.3824***	-0.1633***	-0.2393***	1		
(6)	AUTH	0.0405+	0.1462***	0.0589**	-0.019	0.0011	1	
(7)	AGE	0.1357***	-0.0416*	0.0048	0.1464***	-0.0486*	0.0243	1
(8)	UI	0.0601**	0.0432*	0.0811***	-0.0718***	-0.0826***	0.0887***	0.0296

Note: *** $p<0.001$, ** $p<0.01$, * $p<0.05$, + $p<0.1$

Table 6 Estimation of Poisson regression models (dependent variable: CITE); the effect of authorship on scientific impacts

	(1) ALL	(2) Large impact	(3) Medium large impact	(4) Medium small impact	(5) Small impact
Independent variables					
PASTEUR	0.256*	0.185*	0.0441	-0.0108	0.0355
	(2.61)	(1.97)	(1.13)	(-0.22)	(0.26)
EDISON	-0.297*	-0.314*	0.0170	-0.0396	0.127
	(-2.43)	(-2.54)	(0.38)	(-0.74)	(0.88)
BOHR	0.217*	-0.145	-0.00480	0.0709	0.222+
	(2.02)	(-1.26)	(-0.14)	(1.52)	(1.83)
OTHERS	-0.488*	-0.428*	-0.0234	0.00619	0.200
	(-4.35)	(-3.67)	(-0.58)	(0.13)	(1.51)
Control variables					
AUTH	0.0543*	-0.0319	-0.000646	0.00935	-0.00325
	(2.98)	(-1.49)	(-0.08)	(0.91)	(-0.14)
AGE	0.0453*	0.00898	0.00197	0.00423+	0.0162*
	(10.78)	(1.56)	(0.90)	(1.76)	(3.10)
UI	0.0582	-0.0698	0.0907+	-0.0267	0.130
	(0.48)	(-0.60)	(1.92)	(-0.43)	(0.69)
Intercept	2.651*	4.443*	2.961*	1.956*	-0.101
	(20.89)	(26.60)	(59.89)	(34.35)	(-0.70)
N	1957	495	465	497	500
Log-likelihood	-42739.7	-12405.9	-1407.4	-1161.8	-705.1
Chi-squared	303.9	49.05	11.20	10.39	18.14

t statistics in parentheses
+ $p < 0.10$, * $p < 0.05$

4.3 Estimating the speed of diffusion of the knowledge in scientific community

In order to compare the differences of knowledge diffusion patter, longitudinal trend of forward citation is evaluated according to scientist classification ñBohr scientistsò and ñPasteur scientistsò. We depended on the framework of Jaffe and Trajtenberg (Jaffe and Trajtenberg 1996; Jaffe, Trajtenberg et al. 2000). We model the probability that a particular article *a*, applied for in year *t*, will cite a particular article *A*, published in year *T*. This probability is determined by the combination of an exponential process by which knowledge diffuses and a second exponential process by which knowledge becomes superseded (obsolescent) by subsequent research.

$$p(a,A) = \alpha(a,A)\exp[-\beta_1(t-T)](1-\exp[-\beta_2(t-T)]) + \varepsilon$$

We estimate the above equation using the nonlinear least squares estimation routine of the STATA software package using sample of 1721 articles published in a decade from 1996 to 2006. Due to the limitation of dataset, parameters including citing year, cited year, and technological fields is not yet take into account, however, knowledge diffusion is highly constrained by dynamically changing technological opportunity, those parameter should be incorporated in future analysis. The estimate parameters of current model are shown in Table 7.

Table 7 Citation Function Results

Model	ALL		Bohr		Pasteur	
α	4.48E-06	***	5.31E-06	***	8.23E-06	***
	(14.92)		(12.79)		(7.79)	
β_1	0.0213	*	0.0157		0.0373	*
	(2.10)		(1.28)		(2.03)	
β_2	1.3269	***	1.9268	**	1.0376	**
	(4.79)		(2.77)		(3.10)	
Adj R-squared	0.1247		0.3144		0.1628	
N	15156		2527		4180	

Note: t statistics are in parenthesis *** p<0.001, ** p<0.001, * p<0.05. + p<0.10

In Table 7, model ñALLò shows result from full sample (1721 articles), model ñBohrò limit articles that include at least one Bohr scientist in authors field (281 articles), and model ñPasteurò limit articles that include at least one Pasteur scientist in authors field (452 articles). The citation probability is defined as observed citation count divided by possible citing articles (articles published in year T) times possible cited articles (articles published in year t).

Since the diffusion term (β_2) of ñBohr scientistsò is larger than that of ñPasteur scientistsò, we know that the knowledge produced by the former is more swiftly diffused in academic community, compared to the one produced by the latter. Thus Hypothesis 3 is supported.

5. Conclusion and discussions

When we compare the research performance of entrepreneurial scientists with that of conventional academics, the results of quantitative analysis applied to a sample of 1957 scientific papers published by 66 scientists active in the photocatalysis research in Japan confirm that:(i) whereas the papers published by ñBohr scientistsò entail a good citation performance (much of their papers are frequently cited, and few of them are marginally cited), the papers published by ñPasteur scientistsò entail a relatively poorer citation performance (the proportion of frequently cited papers is lower, and the proportion of marginally cited papers is higher than those published by the latter) and (ii) it takes longer for the ñPasteur scientistsò to get their papers cited than do for the ñBohr scientistsò since scientific contents produced by the former diffuse more slowly in the scientific community. Whereas the findings suggest that prevailing academic entrepreneurship exerts rather negative influence on scientific progress, the Poisson regressions estimation also confirms that ñPasteur scientistsò show higher propensity on break through the scientific frontier by publishing more distinguished papers than do ñBohr scientistsò. Simply put, although the overall research performance of ñPasteur scientistsò are not as good as that of ñBohr scientists", they make a greater contribution to furthering the scientific frontier by publishing more distinguished papers in terms of their impact on scientific community.

Certainly, our findings are due to the specificity of the research subject: in the field of advanced materials, two-way interaction between science and technology provides with scientists the opportunities to extend their scientific research into unexplored areas, and it is the type of entrepreneurial scientists that benefits mostly from the opportunities. Recently, the role of ñPasteur scientists,ò especially those in the field of advanced materials, has become highly esteemed in that their search process can afford to cultivate the unexplored research areas left behind in the march of the traditional ñBohr scientistsò (Kitazawa 2008; Kitazawa 2010). Adam Smithôs combinatorial benefits of knowledge refinement and fragmentation resulting from the division of labor between university and industry are guaranteed by the existence of boundary spanners such as ñPasteur scientistsò(Murray, 2002; Baba, Shichijo, and Sedita, 2009; Metcalfe 2010).

Recently in Japan, as in Europe, state backing of universities has been cut, and public support for R&D is predominantly allocated towards ñoutcome-based basic researchò intended to meet specific needs of society (e.g. solving those problems of global environmental issues, cancer treatment, and an aging society). When allocating shrinking public funds, the ongoing science and technology policy aiming to give priority to research intended to solve societal problems seems relevant by its own sake. However, this paper adds supporting theoretical explanations which enable us to deepen our understanding on the nature of ñoutcome-based basic researchò. In our view, the essence of the policy resides in the search process conventionally pursued by the ñPasteur scientistsò, and while they generate papers that are less likely to be cited in the short term, the papers have the potential to contribute to the progress of science since the papers receive positive evaluations in the long term.

However, we admit the qualification attached to our policy discussion: the same scientists are willing to adopt different search processes depending on their place in scientific community or their position in lifecycle as of a scientist (Stephan and Levin 1992). For junior researchers (i.e. doctoral and postdoctoral students, and assistant professors), the rational strategy will be to begin by adopting the ñBohr-modeò to produce research results quickly and steadily for securing a position in the scientific community. This understanding gives us the caution that labeling a given scientist as a ñBohr scientistò or a ñPasteur scientistò is not an adequate use of the typology for the sake of research policy to tide over tightening competition in scientific community. Having faced with the global trend towards the ñoutcome-based basic researchò policy, this paper promises to provide a preliminary discussion which opens further lines of investigation on the appropriate policy settings which enable scientists to better qualify as proactive actors for both scientific progress and contribution to the society.

Finally, we acknowledge some methodological limits on our study. Since the research was highly focused on a specific industry and nationally bounded, the general applicability of the analysis is limited. First of all, it is likely that the government-driven academic culture recently prevailing in Japan, as well as the idiosyncrasy of an individual scientist, are related to the observed performance divide between ñBohrò and ñPasteurò scientists. It would be necessary to collect the corresponding data from couple of other countries for making sure that the results are consistent across different countries. Similarly, the hypotheses derived from the observation on one specific field are not necessary true to all the scientific fields. Again it would be better if a couple of sub-fields from different areas are included in the study to make sure that the results are robust and consistent. Thus, it is important to note that this argument is not about the divide between ñBohrò and ñPasteurò scientists in scientific contribution generally, but specifically the case of the divide that are 1) based on the specificity of the field of advanced materials, 2) originated and developed mainly in Japan, and 3) with the successful achievements of contributing to the society. Further research is needed to develop the conjecture and to see how the conditions that produce the scientific divide at different countries differ and how each type of scientists contributes to break through the scientific frontier in the long run.

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