The technological paradigm of Nanosciences and Technologies: a study of science-technology time and space relations*

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Abstract

One of the most relevant theoretical insights into the characteristics of technological change is Dosi's technological paradigm. Dosi aims to overcome technology-push and demand-pull theories into a framework closer to facts. The present contribution is set in this framework, aiming to find some evidence, starting from an empirical analysis, of the characteristics of technological paradigms. The context is the *ex ante* and pre-industrialization phase of a highly knowledge-intensive paradigm, that of nanotechnologies and nanosciences. The present work exploits an empirical analysis related to patent citations, with particular regard to citations of scientific journal articles. Both the time and the space dimensions are explored. Results – strict time and space relations between patenting and previous scientific production – confirm some characteristics of technological paradigms envisaged both by the original work and by subsequent literature.

Keywords: technological paradigms, pre-innovative phase, time and space relations, nanotechnologies, nanosciences, patent citations.
JEL classification: O14; O31; O33.

Resumen

Una de las nociones teóricas más relevantes respecto a los cambios tecnológicos es la de "paradigma tecnológico", de Dosi. Éste intenta superar las teorías de la oferta y la demanda alrededor de la tecnología y apegarse a un marco más cercano a los hechos concretos. Esta contribución se inserta en dicho marco e intenta encontrar alguna evidencia sobre las características de los paradigmas tecnológicos, a partir de un análisis empírico. El contexto es la fase *ex ante* previa a la industrialización de un paradigma de conocimiento intensivo altamente especializado: el de las nanotecnologías y las nanociencias. El presente trabajo explota un análisis empírico relacionado con las citas de patentes, en especial con las citas en artículos de revistas científicas, en el cual se exploran tanto la dimensión temporal como la espacial. El resultado confirma – a través de las estrictas relaciones de tiempo y espacio entre las patentes y la producción científica anterior – algunas características de los paradigmas tecnológicos previstas tanto en su planteamiento original como en la literatura subsecuente.

Palabras clave: paradigmas tecnológicos, fase previa a la innovación, relaciones de tiempo y espacio, nanotecnologías, nanociencias, citas de patentes.
Clasificación JEL: O14; O31; O33.

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Introduction and theoretical framing

Social sciences studies have witnessed, since the end of the 20th century, the growth of economic relevance of knowledge-generated externalities (Dasgupta and David, 1994). This has, in turn, originated a growth in the number of studies targeted to deepen the relations between knowledge production, protection of intellectual property and its exploitation in the production of goods.

Among the works, deemed fundamental, that study the characteristics of the value chain going from research to its application, the approach of Dosi (1982) is particularly relevant. Dosi in fact has probably been the first to overcome the stylized models of "technology-push" and "demand-pull". His "technological paradigm" describes in a more realistic way the evolution paths from knowledge to innovation.

In doing so he first established aspects of the innovative process. Among them, the most relevant ones in the context of this work are "the increasing role […] of scientific input in the innovative process […] A significant correlation between R&D efforts […] and innovative output (as measured by patent activity) in several industries" (Dosi, 1982, p. 151). Moreover, he states that "there is a complex structure of feed-backs between the economic environment and the directions of technological change. A tentative theory of technical change should define […] the nature of these inter-active mechanisms" (Dosi, 1982, p. 151). The present works aims to contribute to this definition in an empirical way.

Dosi defines technological paradigms "as 'model' and a 'pattern' of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies […] (it would perhaps be better to talk of 'cluster of technologies')" (Dosi, 1982, p. 152, original emphasis). Finally, the stress posed by the article on "the general weakness of market mechanisms in the *ex ante* selection of technological directions especially at the initial stage of the history of an industry" (Dosi, 1982, p. 155), has to be remarked.

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The present work aims to contribute to the elucidation of this *ex ante* stage, taking into account a specific ("*selected*") set of technologies, that is, a peculiar technological paradigm, and performing an empirical analysis of data. The technological paradigm considered is "in the phase of economic *trial and error*" (Dosi, 1982, p. 157, original emphasis). It can offer some empirical evidence of the *ex ante* stage and of this phase, focusing on the study of how patenting and scientific production are related in time and space in a highly knowledge-intensive technological paradigm.

From the operational point of view, this work seeks to answer two research questions. The first is related to time: how much time does it take for scientific knowledge to be exploited in a patent? The second research question is related to space: how endogenous is the technology exploited in patents to the incorporated science in terms of institution (university, firm, etc) producing science and technology?

An answer to these questions can help scholars to better understand how science and its technological application are interrelated. Patents and scientific articles proxy technological and scientific activity, as defined by Dosi (1982, p. 151). The presence of the "prior art" constraint must obviously be considered. Patents can't cite an artifact that is in some way described in cited literature. Thus the patent-article relation should not be considered in terms of content overlapping, but rather in terms of "technological continuity" between the two documents and the knowledge contained therein.

The specific technological and scientific "paradigm" exploited to perform this study is that of nanosciences and nanotechnologies (NST from now on). NST are a highly knowledge-intensive scientific-technological field. Thus, they were chosen as the main object of the analysis of this work, being a new and emerging scientific-technological sector in growth in all the trajectory going from basic research to innovation.

In order to answer the two research questions mentioned above (and to contribute elucidating science-technology relation in the NST technological paradigm) an experimental activity is performed. Through an apt methodology, it calculates two magnitudes. The first one is the existing time distance between the publication of a scientific article and the registration of a patent citing the article. The second is the measure of the endogeneity between the production of cited knowledge and of citing technology in terms of knowledge/technology-producing institution. Part of the data and of the methodology used in the analysis has been exploited in Finardi (2011).

The considered paradigm belongs to those "more general" paradigms (Dosi, 1982, p. 154). Nevertheless, as will be shown in the experimental sections of the work, the analysis is performed via the use of keywords related to specific NST topics. The methodology collects data on specific "subparadigms", chosen for being deeply representative of the whole and describing its more general trajectory.

The present article is structured as follows. section I contains a review of past literature, divided into four subsections: technological paradigms, definition and history of NST, patent citation analysis, and studies on NST. The second section describes the empirical analysis: methodology and results for the two studies. The last section contains the discussion and the conclusions.

I. Literature review

1. *Technological paradigms*

Several authors have discussed Dosi's technological paradigms in the recent past. This section reviews some relevant recent contributions to frame the context of this article.

Cimoli and Dosi (1995) present a theory of innovation and production, setting their effort into evolutionary microeconomics. To do so, they use the notion of technological paradigm, discussing its implications.

The historical impact of Dosi's work is stated by Von Tunzelmann, Malerba, Nightingale, and Metcalfe (2008). In the authors' opinion, what Dosi did was show that "science-push and market-pull theories of innovation did not exhaust all the alternatives. Moreover, it showed that another, more sophisticated, way of thinking about innovation was possible" (Von Tunzelmann, Malerba, Nightingale, and Metcalfe, 2008, p. 472).

This vision is confirmed by Teece (2008), who asserts that "his paper combined demand-pull and supply push explanations of technological innovation with ideas about how science evolves in waves driven by changing scientific paradigms" (Teece, 2008, p. 508). He also affirms that "technological paradigms impose behavioural structures associated with 'normal' problem-solving activities" (Teece, 2008, p. 509).

Nelson (2008) stresses the science-technology relations in the framework of technological paradigms. He writes, in fact, that Dosi "argued that both understanding closely tied to practice […] and deeper […] understanding of principles bearing on practice, were part of a paradigm, thus recognizing a rough distinction between technological and scientific knowledge and pointing to how they were connected" (Nelson, 2008, p. 485). Moreover, he also highlights the possibility that "scientific knowledge that points to something that can be productively used in a practice […] can provide very useful information to designers. […] advances in basic scientific understanding can sharpen up and provide new insights to the application oriented sciences that draw from them. […] that knowledge [...] provides insights into how artifacts might be made to work" (Nelson, 2008, p. 494, *passim*).

These basic concepts on technological paradigms will be recalled in the discussion.

2. *nst: history and relevant characters*

nst are defined in this way by American National Nanotechnology Initiative: *"Nanoscience involves research to discover new behaviours and properties of materials with dimensions at the nanoscale* which ranges roughly from 1 to 100 nanometres (nm). Nanotechnology is the way discoveries made at the nanoscale are put to work. […] Nanotechnology is more than throwing together a batch of nanoscale materials — it requires the ability to manipulate and control those materials in a useful way" (nni, n.d.).

Balzani (2005) describes the two main different nst approaches ("top-down", typical of physicists and engineers, and "bottom-up", typical of chemists) and their three main areas (nanomaterials, nanoelectronics, bio-nanotech). nst have a strong interdisciplinary and transdisciplinary character, and are set at the convergence point of several scientific and technological fields (Bozeman, Laredo, and Mangematin, 2007; Leydesdorff and Zhou 2007; Avenel, Favier, Ma, Mangematin, and Rieu, 2007). Though they should rather be considered as a set of techniques, nst have gained autonomy as a peculiar scientific-technological trajectory. This is assessed, for instance, by Coccia, Finardi, and Margon (2011); Islam and Miyazaki (2009; 2010) and Huang, Notten, and Rasters (2011).

Nobel Prize Laureate Richard P. Feynman has been the first to advocate the idea of the opportunities offered by intervention at the nanoscale. In December 1959 he pronounced that "There is plenty of room at the bottom". His aim was to describe the possibilities offered by the expansion of science and technology towards the scale of nanometres (Feynman, 1960). Key points of the evolution of nst have been: the invention of Scanning Tunnelling Microscopy (stm) at

IBM laboratories in Zurich by G. K. Binnig and H. Rohrer (1986 Nobel Prize for Physics) (Binnig and Rohrer, 1986); the discovery of Buckminsterfullerene in 1985 by H. Kroto, R. Curl and R. Smalley (1996 Nobel Prize for Chemistry) (Kroto, Heath, O'Brien, Curl, and Smalley, 1985); and the discovery of Carbon nanotubes in 1991 by S. Iijima at NEC Corporation (Iijima, 1991).

NST are now considered fundamental for the future evolution of science, technology, and industrial innovation.

3. *Patent citation analysis*

This section aims to frame the empirical activity reported in this article. Criscuolo and Verspagen (2008) study patent citations as reliable indicators of potential knowledge spillovers. To this purpose, they investigate the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) patent citations. Authors remark the differences between the two systems of citations.

They state that "EPO citations […] can be assumed they have been scrutinized by the patent examiner" and that "in European search reports, cited documents are classified by the patent examiner within a particular citation category according to their relevance" (Criscuolo and Verspagen, 2008, p. 1895, *passim*). Moreover, "the European patent database allows identification of whether citations are added by the applicant/inventor (inventor citations) or the patent examiner" (Criscuolo and Verspagen, 2008, p. 1907). Thus, on the basis of the EPO database, "we found evidence that geographical distance has a negative impact" (*ibidem*).

Mechanisms of knowledge diffusion by Universities and Public Research institutions in Europe are described by Bacchiocchi and Montobbio (2009). They select patents registered between 1978 and 1998 in several countries and technological areas. Results show that knowledge "incorporated" in patents coming from Public Research Organizations is more cited than that present in corporate patents. This fact is more accurate for the United States of America (USA) in some sectors (Chemical, Drugs & Medical and Mechanics) and less accurate for European Union (EU) countries.

The existing links between science and technology have been traced by Breschi and Catalini (2010) using citations of journal articles in patents. Their empirical analysis draws on names of researchers/inventors, analyzing their presence in both networks of scientists and technologists/inventors. Results show interconnections between the two communities, with an important role of individuals (Breschi and Catalini, 2010, p. 24).

Schmoch (1993) performs an analysis of non-patent citations in patents, quantitatively describing the relations between science and technology. He distinguishes different types of citations in EPO procedures. Results assess two characteristics of this relation: there are many kinds of links between citations and patents; non-patent citations may be caused by different factors. Moreover, he states that "there exists only plausible support for the hypothesis that a high number of non-patent citations can be considered as an indicator for a strong science interface" (Schmoch, 1993, p. 210).

Meyer (2000a) describes the role of citations and their different types exploiting the methodology assessed by Schmoch (1993). He performs a case study analysis assessing science links, knowledge flow directions, and national differences.

Peculiar characteristics of patent citations with respect to scientific citations are assessed by Meyer. The reality of patent citations is complex and multifaceted and it depends on the examining practices (Meyer, 2000b, p. 111 and hereafter). Differences between procedures from USA and EU are pointed out in their outcome.

The study of patent citations allows Sternitzke (2010) to assess the innovation characteristics of pharmaceutical industry. In particular, the assessment is performed on the existing differences between radical and incremental innovation, and between technological and market breakthroughs. No time analysis is performed in this study.

4. *Bibliometric studies on NST: an historical perspective*

This section reviews a selection of literature regarding bibliometric studies on NST, paying particular attention to those discussing patents. Given the short historical path of this technological trajectory it seems meaningful to sort the cited works chronologically, to follow the evolution of the topic.

Meyer (2001) studies citations of journal articles in nanoscience and nanotechnology patents. The database is relatively small, as it encompasses patents issued from 1976 to 1999 and journal articles published between 1991 and 1996; in those years, NST were at a very early stage. Results support the idea that, at that point of the historical path of NST, science and technology were mostly separate activities, with a much mediated relation, in a sort of a twobranched structure (Meyer, 2001, p. 181). A further analysis has been done by Hulmann and Meyer (2003); findings show, again, limited interactions between nanoscience and nanotechnology.

Glänzel and Meyer (2003) retrieve citations of USPTO patents in journal articles indexed in the Science Citation Index in 1996-2000. Results show a much higher quantity of patent citations in chemistry journals than in other scientific areas.

Li, Chen, Huang, and Roco (2007) perform a network analysis on a sample of USPTO patents retrieved with a "full text" query to study NST patents' citations networks. Findings show that the most citations are of USA patents; in general, citation networks show a very large core component encompassing the bulk of the nodes; different national networks have different knowledge transfer efficiencies and tend to form local citation clusters.

In another work Li, Lin, Chen, and Roco (2007) compare USPTO patents with EPO and Japan Patent Office (JPO) patents. Their findings show that NST patents grow quasi-exponentially. Similarities and differences between inventors' countries and NST fields are studied.

Hu, Chen, Huang, and Roco (2007) perform a longitudinal study of NST patent citations to academic literature. The study identifies two main fields of scientific research: chemical/pharmaceutical and material/semiconductor. The majority of citations are relative to a small number of journals. The information provided by journal article citations present in patents can be exploited to assess the impact of academic research on innovation; this is particularly accurate for an emerging area such as NST.

Leydesdorff and Zhou (2007) study patents from the (then) new USPTO class 977. The database is composed of 336 class 977 patents classified by USPTO in 2005.

From these patents, non-patent literature references are extracted and studied. According to their conclusions, "references to the scientific knowledge base of the patents are not specific enough for the delineation of a core set of nanojournals" (Leydesdorff and Zhou, 2007, p. 708).

Leydesdorff (2007) studies instead EPO Y01N class patents (nanosciences and nanotechnologies), together with a further analysis of journals. From this, analysis using the new patent tag in order to retrieve data on NST is assessed.

Bonaccorsi and Thoma (2007) touch upon the topic of patenting in NST, focusing on USPTO patents from 1971 onwards, and investigate science-technology relations. Their results show that knowledge production in the field is faster than the average, that there is turbulence in the growth pattern and a "tremendous" (Bonaccorsi and Thoma, 2007, p. 829) impact of scientists on patenting.

Wang and Guan (2010) study the role of NST patenting among researchers and its effects towards scientific production. Their study, performed through the use of a Poisson model, shows the positive impact of patenting towards publications.

II. Experimental section

1. *Methodological framework*

In order to provide evidence of some of the existing mechanisms in technological paradigms, the present work performs an experimental activity. This activity measures two magnitudes. The first one is the time lag existing between the filing of a patent and the scientific literature it cites. The second one is the fraction of cited scientific literature endogenous to the group of institutions producing citing patents.

In the analysis of NST technological trajectory, the amounts of journal articles and patents respectively proxy the production of knowledge and its pre-applicative use. It is not possible to say that patents proxy innovation. In fact, no information on the exploitation of patents is used, and thus no conjectures on technology application can be made. It must also be noted that patent citations can be added either by patentees or by patent examiners, but the studied dataset does not allow to distinguish between the two types of citations.

The two magnitudes are measured to answer to the two questions mentioned in Introduction about the time it takes for scientific knowledge to be exploited in patents and its endogeneity. In this manner, it is possible to shed some light on the existing mechanisms in specific highly knowledge-intensive technological paradigms in their pre-applicative phase.

Methodology is based on the number of citations of scientific journal articles in patents. Data mining has been performed on the SciFinder Scholar database (described in Appendix 1). This database was chosen because of its completeness and restriction to the sole fields of interest of this work. The data mining procedure retrieved data on the year of publication of cited scientific articles and citing patents, and on the affiliation of applicants and authors.

The study has been performed taking in account several specific NST relevant topics. These ones belong, in turn, to several typologies. This was done to describe NST under a wider perspective, through the analysis of several "sub-paradigms" as is described above.

The studied topics are as follows: three classes of nanostructured materials of main importance (Fullerene, Nanoparticle, and Nanotube); a technologically relevant material in one of its nanostructured forms (Mesoporous for Mesoporous Silica); NST-related study and analysis techniques (AFM- Atomic Force Microscopy, STM - Scanning tunnelling microscopy); the nano-pertinent term Biosensor (Porter, Youtie, Shapira, and Schoeneck, 2008).

The data mining procedure has been performed using sets of search terms for each studied item, to obtain a precise and complete dataset. Table 1 lists the sets of search terms for each NST topic. Appendix 2 contains the detailed description of data mining procedure.

Table 1. *Search terms for SciFinder queries*

AFM, Atomic Force Microscopy, Atomic force Microscope
Biosensor, Bio Sensor
Fullerene
Mesoporous, Mesopore
Nanoparticle, Nano particle
Nanotube, CNT
STM, Scanning Tunneling Microscopy, Scanning Tunneling Microscope

2. *Time analysis: methodology and results*

For this analysis, two sets of data have been retrieved for each group of keywords. These are the number of patents per year and the number of cited scientific articles per each patenting year, subdivided according to the year of publication of cited articles. Data have been analysed in two steps.

In the first step, the average number of citations per patent was calculated for each year. Then, the averages were summed according to the time distance in years between patenting and publication of the cited journal.

In the second step, time lag series were calculated. The year of patenting was considered year "0" for each year taken into account (from 1998 to 2006). Averages obtained in the first step were, thus, summed up according *not* to the year of publication, *but* to the time lag existing from publication to being cited.

This was done starting from this point (that is to say, cited articles published in the same year of patent) and going back to year -20 (that is, patents citing articles published 20 years before being issued).

Analytically, given (for each item) a = 1998 to 2006, then PAT_a = number of patents issued in year a. Given b = 0 to 20, then $CITJOU_{a-b}$ = number of journal articles cited in PAT_a and published in year $a - b$.

From these definitions, we derive the equations used in the calculation:

$$AVG_{a-b} = \frac{CITJOU_{a-b}}{PAT_a}$$

and then (for each b)

$$SUM_{-b} = \sum_{a=1998}^{2006} AVG_{a-b}$$

The values of SUM_{-b} for each $-b$ year are the final result of this analysis. Years ($-b$) presenting the two highest values of SUM_{-b} are considered the most relevant time lags between cited articles and citing patents (that is, between codification of knowledge for scientific purposes – article publication – and its codification for technological purposes – filing of patent). Results are reported in Table 2 for each topic: time lags ($-b$ in years) and SUM_{-b} (average citations of articles). The shorter the lag, the higher the speed of inclusion of related scientific knowledge in the patented technological output.

Table 2. *Time analysis results*

Item	1st Maximum		2nd Maximum	
	$-b$ (years)	SUM_{-b} (average citations)	$-b$ (years)	SUM_{-b} (average citations)
AFM	– 3	1.28	– 5	1.15
Biosensor	– 3	0.88	– 4	0.73
Fullerene	– 7	0.63	– 3	0.55
Mesoporous	– 4	1.07	– 3	0.79
Nanoparticle	– 4	0.65	– 3	0.62
Nanotube	– 3	0.98(4)	– 2	0.98(1)
STM	– 5	1.01	– 4	0.7

For six out of seven topics the most representative time lag is –3 or –4 years previous to the patent. For the other value of average citations the same time lag is present in five out of seven cases. The remaining values are –2 in one case, –5 in two cases and –7 in one case. Thus the most representative time lag between publication of cited articles and patenting of citing patents lies in the 3–4 years range. It must also be taken in account that this encompasses the procedure of preparation and evaluation of citing patents.

3. *Spatial analysis: methodology and results*

The study of endogeneity of cited documents was realized on patents registered in year 2006 (the last studied year) for each NST search term. Data about applicant institution of citing and cited patents, and about author affiliation of cited journal articles, were retrieved. Affiliations were preferred to names in order to bypass homonymy problems. For each applicant of citing patent, applicants and affiliations of cited documents were retrieved.

Two measures were calculated from the obtained data: percentages of endogenous documents (fraction of cited documents generated from affiliations, which also generated citing patents); percentages of applicants/affiliations producing endogenous documents. Results are reported in Table 3.

Table 3. *Data on spatial analysis*

Keyword	% endogenous articles	% affiliations producing endogenous articles	% endogenous patents	% affiliations producing endogenous patents
AFM	32.6	18.3	24.5	15.8
Biosensor	8.0	5.7	22.2	13.9
Fullerene	18.4	16.3	34.9	23.2
Mesoporous	18.8	12.2	20.2	15.7
Nanoparticle	32.7	22.1	32.7	18.9
Nanotube	30.0	32.6	71.2	62.8
STM	5.6	6.3	12.7	9.9
Average	20.9	16.2	31.2	22.9

Percentages of endogenous cited articles are equal or over 30% in three cases, below 20% in two cases, and below 10% in two cases. Data for endogenous cited patents go from 12.7% to 71.2%, and the average is much higher than that of journals (31.2% *vs.* 20.9%). Percentages of affiliations producing endogenous cited documents show their concentration.

Data also show that endogenous patents are more cited than endogenous scientific products. The rather high endogeneity of cited documents is notable: in average, 20% of cited scientific products and 30% of cited patents are derived from patenting institutions.

In order to deepen this analysis, public (state) owned research bodies and companies/private research institutes were considered independently. Citing patents were divided according to this determinant, as well as cited documents (patents and articles). Table 4 reports the results for private bodies; the other group sums up to 100%.

Results show that companies/private research organization produce the most part of citing patents and cited patent. Public research bodies, instead, produce more cited articles and patents citing articles.

Table 4. *Spatial analysis – typology of patenting/publishing body*

Keyword (data for each field in 2006)	% citing patents from private bodies	% cited articles from private bodies	% cited patents from private bodies
AFM	64.2	17.0	84.1
Biosensor	74.7	0.0	72.7
Fullerene	74.0	21.0	68.0
Mesoporous	50.0	2.1	57.3
Nanoparticle	55.8	6.0	74.9
Nanotube	61.7	22.2	67.6
STM	92.9	0.0	100.0
Average	67.6	9.6	74.9

III. Discussion and conclusions

The main target of the present work was adding evidence to the existing mechanisms in the *ex ante* selection of technological directions in a highly knowledge-intensive specific technological paradigm, that of Nanosciences and Nanotechnologies. To this end, it seeks an answer to research questions about the time and space distance between the production of science and its incorporation into a patented invention. To seek this answer, it describes an empirical activity based on patent citations of scientific articles relative to several relevant items representative of NST.

The empirical activity was performed measuring two quantities. The first one is the existing time lag between publication year of patents citing scientific publications and of the cited documents.

This lag proxies the time lag existing between the production of the results of scientific activities and their incorporation in a technological outcome. The second one is the fraction of cited documents endogenous to the institutions (firm, company, research centre, university, etc) producing the citing patent. This measure is intended to proxy how much of the knowledge incorporated in the patents is derived from the same source.

Experimental results show that the most relevant time lag between scientific publication and patenting is around 3-4 years. This time lag is quite short, especially if we consider the technical timing of publishing and patenting. All studied items present a similar behaviour: this allows us to think that this behaviour is generalized for NST.

Endogeneity of documents cited in patents is rather high: around 20% of cited scientific products and 30% of cited patents are produced by patent applicants. The analysis of disaggregated data shows that most citing patents (67%) have been produced by companies or private research centres, while only the remaining 33% by state/public research centres/Universities. At the same time, the first group of patentees cite their own patents (an average of almost 75%) more than their own scientific products (less than 10%). The opposite is true for the patents of the second group.

A first interpretation of these facts is the following: scientists tend to patent the discoveries made during their basic scientific research activities. The short time lag supports the idea that scientists also tend to develop technological application of research as soon as a new discovery is made. Once a technical application of a scientific discovery is envisaged, scientists might be able to proceed along two pipelines, also avoiding possible problems for patenting due to the creation of a prior art.

These facts might be particularly accurate for scientific institutions that tend to privilege basic scientific research rather than applied fields. This idea is supported by the fact that more than 90% of endogenous (deriving from patenting institutions) scientific products have been originated in patenting (public) scientific institutions. Conversely, companies cite more their own technological productions (patents).

Some caveats must, indeed, be taken into account. Regarding time analysis, it must be noted that some patent offices accord a "grace period" to patentees (*e.g.*, one year for USPTO, 6 months for JPO). The presence of this grace period might have effects on the temporal evolution of patent citations.

Regarding the space analysis, it must be taken into consideration that names of corporations might, in some cases, be ambiguous (though due care has been taken in controlling data). Also, the presence of subsidiaries entrusted with intellectual property might cause problems. Nevertheless, subsidiaries whose name is related to that of the owning institution have been grouped with it (*e.g.*, foundations or the trustees of a University).

It must also be taken in account that patent citations can be added either by patentees or by patent examiners. When citations are added by authors we can assume that institutions/authors producing patents tend to cite their own scientific/technological knowledge.

In this case, calculated percentages give us a measure of the origin of cited knowledge: the highest the percentage, the highest the quantity of endogenous knowledge cited. In the other case (citations added by a patent office), the relation is less direct. Our dataset does not allow distinguishing between the two kinds of citations.

Finally, to respond to the main target of this article, results are interpreted in the framework of technological paradigms. Findings support Dosi's statements on technological paradigms, and the concepts reported from literature in section I.1. Strong temporal and spatial interrelations presume the presence of a set of cognitive and functional relations inside organizations. This might be strictly connected to normal problem solving activities (see Teece, 2008). This might also be associated with the production of scientific knowledge useful for designers of technologies, as pointed out by Nelson (2008).

Experimental results also confirm the correlation between R&D and innovative output (proxied by patenting) stressed by Dosi (1982) as one of the basic facts underlying his theory. In a growing and highly active field such as NST, overlapping of R&D and innovative output might be one of the driving forces of the selection processes put into action in the economic *trial and error* phase (see Dosi, 1982, p. 157). This result should be coupled with the differences existing between firms ("previous technology" vs. "new technology" overlap) and research centres ("science" vs. "new technology" overlap). These might be the "economic criteria" (Dosi, 1982, p. 153) acting as selectors of a new technological paradigm.

Appendix 1. Description of SciFinder Scholar

SciFinder Scholar is a database of Chemistry and Materials sciences documents. It is maintained by the American Chemical Society (acs). acs collects and publishes data from 1907 onwards (abstracts and full bibliographic reference) of any piece of knowledge (such as journal articles, patents, congress contributions, etc) related to its relevant specific topics. It does so through its Chemical Abstract Service (cas), which also publishes full indexes of the documents reported.

The number of journals collected in cas is not reported; nevertheless the most important ones (more than 1500 journals) are reported within seven days after publication. Patent data are collected from 61 patenting authorities; those from the nine most important ones are reported within two days from their issuance. The full database has been made available online, and is a valuable resource for libraries of research institutions of Chemistry and related subjects, also due to its very high cost of subscription.

Appendix 2. Description of data mining procedure

Data mining has been performed on SCI Finder using the following procedure (after assessment and choice of keywords):

1. Search in “Research Topic”
2. Filtering of document type “Patents”
3. Retrieval of patents containing the chosen keyword with the option “As entered”, always using the “Remove duplicates” option
4. Division of patents according to the registration year considering patents registered between 1998 to 2006 (SCI Finder records contain no data on citations in documents published before 1998);
5. Retrieval of cited reference for each group of patents (keyword-year)
6. Division of references according to their kind (patents, journals) and further division according to the year of publication

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