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Running ahead in the nanotechnology gold rush. Strategic patenting in emerging technologies

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ABSTRACT

This paper provides theoretical and empirical contributions on how patent scope varies over time and by type of applicants in the initial phases of an emerging technology. We refer to the literature on technology life-cycles and on appropriability regimes in order to study the evolution of patent scope – as measured by the number of claims – in the specific case of nanotechnology. Our regression analyses, based on a sample of 58,244 nanotech US patents, show that – once time, sector and firm effects are controlled for – patent scope decreases over the subsequent phases of the technology life-cycle. Moreover, we find that university nanotech patents tend to be characterized by a broader scope than other patents. We conclude by discussing the managerial and policy implications of our empirical results.

1. Introduction

The history of past technological revolutions over the last two centuries – as in the case of electricity generation, telecommunications, software and biotechnology for example – shows that the emergence of major technological discontinuities tends to initiate an era of ferment in which both new entrants and established corporations flood into the market to exploit the promises of the new technologies [40,84,86]. In many cases, this period is accompanied by a real "boom" in patent filings, as companies strive to stake exclusive property rights over inventions that could have wide-ranging applications in the future [3,30].

The race to enter early and patent intensively and broadly in a new, fast evolving and highly uncertain landscape has often been compared to the earlier California "gold rush" of the nineteenth century. However, this phenomenon has also raised concerns that a proliferation of patents, especially broadly defined ones, could produce a thicket of conflicting legal claims, which could ultimately slow innovation rates and raise costs for companies and consumers due to increasing legal disputes [4,8,32].

The question of appropriate patent scope in the early stage of a new technology, and how this can change over time as the technology matures, thus represents an important condition for fully understanding the evolutionary and competitive dynamics of an industry. Previous literature on this issue has been mainly based on historical qualitative evidence, referring to pioneering patents in specific industries [53]. To our knowledge, the only quantitative studies that have empirically analyzed the evolution of patent scope in emerging industries are those of Lerner and Merges [46] and of Haupt et al. [30], respectively concerning biotechnology and software, and pacemaker technology. However, these studies suffer from some limits as to the definition of the different phases of the technology life-cycle, the identification of relevant patents and the lack of control for more general trends in patent scope. In addition to that, no

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previous studies have tried to analyze whether the propensity to stake broad patent claims in an emerging technology varies according to the nature of the applicants.

In order to fill such gaps, this paper intends to provide theoretical and empirical contributions on how patent scope varies over time and by type of applicants in the initial phases of a new technology life-cycle. We refer to the literature on technology life-cycles [7,40,77,86] and on appropriability regimes and strategic uses of patents [10,23,47,80] to argue that: 1) the propensity to file broad patents significantly varies over the different phases of a novel technological field; 2) the observed changes in patent scope over the life-cycle of the new technology differ once the more general increase in the scope of patents observed over the last decades and across sectors is controlled for; and 3) there are significant differences in the breadth of patents filed by companies as compared to other types of applicants (in particular universities and public research centers), as a consequence of differences in the simplicity and complexity of underlying inventions.

Empirically, we focus on the case of nanotechnology, given that it provides a clear example of an emerging technology [51,54,75,90] and we analyze a unique dataset of all nanotechnology patents issued at the United States Patent and Trademark Office (USPTO) in the period 1976–2005, corresponding to 58,244 patents. Following previous literature, we measure patent scope in terms of the number of claims included in the patent [43,81,87]. Moreover, we compute time and industry-adjusted indicators of patent scope, in order to control for the dynamics in patent filing strategies over time and across sectors [88].

Our paper provides the following additional contributions to previous literature. First, the adoption of a novel and comprehensive database allows us to identify all nanotechnology US patents and measure their scope, both in absolute terms and in comparison to a wider set of science, as well as technology patents filed in the same years and in the same sectors. In this way, we are able to control for various factors which may affect the evolution of patent scope, as suggested by previous research [27,87]. Second, our paper investigates whether the scope of patents varies with respect to the type of applicants. We argue that different patenting institutions might have different capacities and incentives to stake broad patent claims in the early days of a new technological trajectory.

The rest of the paper is organized as follows. Section 1 presents the theoretical framework. Section 2 describes the context of our study – nanotechnology as an emerging technological field – and the different approaches to identifying nanotechnology patents. Section 3 discusses the dataset, the variables and the methods applied in our empirical study. Section 4 shows the findings of our analyses and Section 5 presents additional robustness checks. Finally, Section 5 discusses the theoretical and managerial contributions of our study and some indications for future research.

2. Background

2.1. Technology life-cycles and patenting activity

According to technology life-cycle theories, technological innovation proceeds along well-defined cumulative and path-dependent technological trajectories. Technology life-cycle models argue that technology development and the degree of market competition vary across different phases of the life-cycle [2,13,15,40,77,86].[2] A recent review of the literature on technology life-cycles has highlighted numerous contributions which can be grouped into two main perspectives – the so-called macroview and the S-curve – characterized by a multiplicity of terminologies used and by the identification of different stages [79]. The former perspective is concerned with the macrolevel of technological progression and technological trajectories [2,58,86]. According to such view, a technology cycle begins with a technological discontinuity, i.e. a breakthrough innovation affecting either a product or a process,[3] followed by a period of ferment during which competition among variations of the original breakthrough eventually leads to the selection of a single dominant configuration [1,2,58,86]. Following the emergence of the dominant design, an era of incremental evolution of the selected technology constitutes the remaining stage of the cycle, up to the eventual emergence of a further discontinuity.

Studies grouped under the S-curve perspective, on the other hand, have highlighted that technological progression in the majority of cases conforms to the general form of an S-curve [13,14,19,28,30,67], since it typically “advances slowly at first, then accelerates, and then inevitably declines” ([19]: 20). Patenting activity seems to follow similar patterns of development across the different phases of a new technological trajectory. Existing studies in a variety of emerging technologies, such as antibacterial medicines [3], pacemakers [30] and CNC technologies in the machine tool industry [17], suggest that the number of patent applications seems to follow an S-curve distribution in the various phases of the technology life-cycle. In the introductory phase of a new technology's development, the number of patent applications tends to be low and only increases slowly and to be typically concentrated in a limited number of pioneering firms. As the technology enters the growth phase, and major technical and market uncertainties are resolved, there is a rapid growth in the number of patent applications, which tends to level off as the technology matures and the opportunities for product innovation diminish. Moreover, it is not only the number of patent applications that changes over the different phases, but also the filing strategies and the characteristics of filed patents [30].

A characteristic that has received particular attention in the literature is patent scope, defined as the breadth of protection provided to the applicant by the patent claims [45,52,56,89]. The innovator, through the number and the nature of claims made in the patent application, specifies the technological territory over which protection is claimed. The economic value of a patent thus inherently depends on its scope, given that competing products and processes have a higher likelihood of infringing patents characterized by broad claims [45,52,56]. Therefore, the choice of patent breadth is a strategic decision for the innovator, especially in the early days of an emerging

[2] A detailed review of the literature on technology life cycles is beyond the scope of this article. A recent and exhaustive review of this stream of literature is provided by Taylor and Taylor [79].

[3] The innovations representing a discontinuity are also labeled in this literature as revolutionary, breakthrough, radical, emergent, paradigm changes [79].

technology. This has important implications for its ability to safeguard and defend its technological territory [89,76].

As a consequence, the Patent Offices' decisions to grant broad patents in the early phases of a technology life-cycle might significantly affect the subsequent evolution of the industry. Previous literature [52,55,59] has provided several examples of the effects of patent scope decisions on industry structure and innovation rates, generally referring to rich qualitative descriptions of specific pioneering inventions. For instance, the basic patent issued in 1880 to Thomas Edison covering the use of a carbon filament as the source of light, represented the cornerstone for the development of the American incandescent-lamp industry, and gave Edison's company (which later became General Electric) a dominant position in the industry [55]. The patent granted in 1988 to the inventors of a transgenic mouse, incorporating a claim to any "non-human mammal" made with their procedures, guaranteed the possibility of exploiting the invention in a wide variety of application fields [59].

For such reasons, it has been noted that first inventors have strong incentives to stake broad claims in the early days of a technology life-cycle, in order to safeguard their inventions from infringements and thus increase their innovation's rents [46,52]. Early in the history of a technology, there is a higher possibility (and the potential benefits are higher) of obtaining broad patents, due to the absence of competing inventions, the high uncertainty about the market applications and the limited understanding of the prior art landscape by patent examiners. In addition to that, the vocabulary of more recent technologies may be less standardized than in more established fields, thus requiring more detailed descriptions and explanations in the drafting of the patent [25,87]. On the contrary, as the technology matures and becomes more codified, there should be a narrowing of patent scope, driven by the increasing amount of prior art, by the improved codification of key-concepts and search terms, and by the higher likelihood of infringements and patent validity challenges by competitors.

The abovementioned considerations suggest that in the early growth phase of an industry's technology, patent applications should present a higher scope, whereas the breadth of protection should narrow significantly over time.

Despite the importance of the optimal breadth of patents for the dynamics of industry evolution and for the firms' strategic choices, however, there is a surprising lack of systematic empirical evidence in the literature on this topic. With the exception of descriptive accounts of specific industries and pioneering patents [52], to our knowledge only two studies have empirically measured how the scope of patent protection has evolved over time in the different phases of a technology life-cycle.

The first one is the paper by Lerner and Merges [46] on the biotechnology and software industries. They identified biotechnology and software patents over the period 1981–1993 as those granted to firms specializing in these fields. Such firms, in turn, were identified by two sources: 1) the records of Venture Economics to select VC-backed companies in software and biotech; 2) the Compustat records to identify firms and research companies active in the primary industry categories related to software. The analyses of Merges and Lerner show a significant narrowing over time in both industries of the breadth of patent protection, as measured by the number of IPC classes (4 digits) in which the patent is assigned. However, the sampling procedures adopted in this study present some constraints that might affect the significance of the results and limit the scope of the analyses. First, as a result of the sampling process, it is possible that the composition of investigated patents is biased towards new technology-based, VC-backed companies. Patents assigned to universities, for instance, are probably absent in this study, although academic patenting can play an important role in science-based fields, such as biotechnology. Second, the association of patents to specific industries starting from standard industrial classification is problematic, given the lack of correspondence between IPC classes and SIC (or Venture Economics) classes.

The second paper by Haupt et al. [30] analyzes the evolution of different patent indices in the various phases of the life-cycle of pacemaker technology. In this study, the breadth of patent is measured through the number of dependent claims included in each patent, and the findings are in contrast with previous argumentations. They find a statistically significant increase in the average number of dependent claims included in the patent in the maturity phase as compared to the growth phase, but no significant differences in the first stage transition.

The existing empirical evidence on the evolution of patent scope across the different phases of a technology life-cycle is therefore scarce and controversial. Besides that, it presents both conceptual and methodological limits. Conceptually, existing studies seem to assume that the reduction in patent scope, as the technology matures, simply descends from the accumulation of technical knowledge and patent literature that gradually overcrowds the technological space. In this view, the growing body of "prior art" almost automatically limits the sweep of patent claims, making broad patents increasingly rare.

However, this view seems to ignore the fact that, from the applicants' point of view, patent scope choices are not mere technical decisions, but increasingly represent strategic decisions which might confer sustainable competitive advantage over competitors [9,23,28]. This shift of perspective is fundamental to understanding that patent scope decisions "[…] depend heavily on technology-specific practices and their evolution over time" ([88]: 542). In particular, an investigation of their dynamics should carefully control for the dramatic increase in the size and breadth of patent applications over the last decades, largely due to changing legal, technological and market conditions [87]. However, existing empirical evidence on the evolution of patent scope in emerging technology has in large part overlooked controlling for these other forces. This can be a primary reason for the lack of convincing and stable results.

Finally, it is likely that various types of institutions have a different behavior towards advancing broad patent claims in the early period of a new technological revolution. Existing studies, however, do not differentiate between various types of applicants in the propensity to file broad patents as a new technology emerges and matures. In the next section, we will discuss in more depth such existing gaps in the literature, and specify our contribution on how to address them.

2.2. Strategic patenting in emerging technologies

The well-documented surge in patenting activity since the '80s [41] has been attributed by several authors in large part to an increased propensity of firms to patent for strategic reasons [4,23,28,41]. The literature on appropriability regimes has emphasized that patents are not only used to defend proprietary inventions from the imitation of competitors, but are increasingly used for strategic reasons, such as blocking competitors from developing rival technologies, or to ensure themselves the freedom to operate without infringement, or to aggressively impose their bargaining position in negotiation [10,47,80]. All these tactics induced by strategic interactions with competitors have not only generated more patent applications over the last decades, but they have also significantly changed the design of patents and the drafting styles [5,23]. Previous work has documented the existence of different forms of patent filing strategies increasingly used by applicants in an attempt to reinforce the legal strength of their patents, circumvent disclosure requirements or, in more controversial cases, create uncertainty in a specific area [88]. They range from the form and quality of the drafted document (i.e. the number of claims filed), the construction of patents by assembly or disassembly, and the filing of divisional applications, to the route chosen to reach the EPO (via the PCT process or not) and the request for accelerated search [88].

In light of this literature, therefore, it becomes clear that the number and breadth of claims introduced in the patent are strongly influenced by a series of institutional, technological, market and strategic factors that should be well considered in the empirical analyses. The study of van Zeebroeck et al. [87] on a sample of more than one and a half million EPO applications filed between 1982 and 2004 documents the evolution of drafting practices and identifies the underlying determinants. First, it shows a dramatic surge in the number of claims per patent over time, moving, on average, from around 10 claims per EPO application in 1980 to roughly 29 claims in 2004. Second, it highlights that the geographical origin, the degree of technological complexity, the emergence of new sectors and patenting strategies all play a significant role in explaining the size and breadth of patent applications.

These results have therefore critical implications for the study of the evolution of patent scope in emerging technologies. From a conceptual and methodological point of view, the analysis of the variation of patent scope in the different phases of the technology life-cycle should be well distinguished by a series of other influencing factors. However, existing empirical evidence has largely ignored addressing such issues. We therefore intend first to address this gap by reformulating and testing more rigorously the predictions of the literature on the evolution of patent scope in emerging technologies, as follows:

Hp. 1. *Controlling for time-, sector-, firm- and invention-level factors, the scope of patents decreases as an emerging technology matures over its life-cycle.*

In addition, the broader literature on appropriability regimes and strategic patenting also suggests that the propensity to stake broad patent claims in an emerging technology could significantly vary with the nature of the applicants [9,27]. In particular, given that the birth and development of many important technological breakthroughs have been promoted by inventions created by academic scientists [59,62,68,92], it is interesting to consider potential differences between corporate patents and university patents (or patents generated by public research organizations). Previous research has highlighted that patents generated by corporations and by universities are dissimilar in many different ways [12,34,72,82]. Using a large sample of university and corporate patents, Trajtenberg et al. [82] found that the former obtained higher values of importance of innovations, generality of research outcomes, and of reliance on scientific sources, as a consequence of the stronger focus on basic research of universities as compared to corporations. The study by Sapsalis et al. [72], on a sample of EPO patents from Belgium, shows that the value distribution of university and corporate patents is similar, although most valuable corporate and academic patents are the ones citing patents that are invented by public institutions. Similarly, the analysis by Czarnitzki et al. [12] based on a sample of German academic patents shows that short-term forward citations are associated with corporate ownership, while long term citations are linked to university ownership. Moreover, they find that university-generated patents issued to corporations tend to have a narrower scope (as measured by number of IPC classes) as compared to inventions that are patented by the universities themselves. They interpret this result as being due to the fact that corporations tend to source knowledge from universities that yield immediate returns and tend to ignore more basic patents that result in later applications.

Despite that, to our knowledge no previous work has compared corporate and university patents in terms of patent scope in the specific case of emerging technologies. Based on the abovementioned literature, we argue that, in emerging technical fields, patents by corporations should be characterized by a more limited scope as compared to university patents. Given that university patents tend to rely more on recent science, they should be characterized by a broader scope of potential applications than corporate patents, especially in new, science-based technological areas, such as biotechnology or nanotechnology. We thus expect the following:

Hp. 2. *Controlling for time-, sector-, firm- and invention-level factors, in an emerging technology the scope of corporate patents is lower than the scope of university patents.*

3. The context

3.1. Nanotechnology as an emerging technology

Nanotechnology can be defined as the study and use of the unique characteristics of materials at the nanometer scale, between the classical large-molecule level to which traditional physics and chemistry apply and the atomic level in which the rules of quantum mechanics take effect [44]. It is not easy defining the founding date of the nanotechnology field. Some seminal research started in the 1950s, but the major scientific breakthroughs go back to the 1980s, when the term nanotechnology was adopted for the first time to identify this technological area. In terms of technological breakthroughs, scanning probe microscopy was one of the key innovations, discovered in 1981 by Binnig and Rohrer at the IBM Research Laboratory in Zurich, which made nanotechnology one of the most important and promising areas of physical science research [38]. The popularization of a conceptual framework for the goals of nanotechnology began with the 1986 publication of the book Engines of Creation by K.E. Drexel, which popularized the concept "nanotechnology" originally coined by the researcher Norio Taniguchi in 1974.

Following such historical process, nanotechnology has emerged as a distinctive scientific and technical area, characterized by a variety of sub-fields and application domains. A first peculiar characteristic of nanotechnology resides in its interdisciplinarity, attracting scientists from many areas of science with a main focus on materials science (and chemistry and physics), but with a significant involvement in many other fields, including biomedical sciences, computer sciences and math, environmental sciences, and engineering, among others. In addition to that, nanotechnology is also characterized by a wide spectrum of potential market applications, which can involve very different businesses (such as computers, flat-panel displays, diagnostic products sensors, lighting devices and many others). According to recent estimates, the number of nanotechnology products proposed on the market has increased from 210 in 2006 to 800 in 2010 and their revenue is expected to grow from $2.3 billion in 2007 to $81 billion by 2015 in the global market [85].

For these reasons, when compared with other traditional technological fields, nanotechnology is a really peculiar and different area. Porter and Youtie [64], for instance, developed empirical measures to evaluate the extent and nature of interdisciplinary interchange in this field, using "science overlay maps" of articles, and their references. The results suggest that "nanotechnology research encompasses multiple disciplines that draw knowledge from disciplinarily diverse knowledge sources" (including materials science, physics, chemistry, biology, mathematics, and engineering) and that "nano research is highly, and increasingly, integrative" ([64]: 1023). Other authors spoke about convergence, in the sense that it brings together different sciences and technologies into a single field [50,74] and cross-disciplinarity [22]. According to Youtie et al. [90], nanotechnology is also defined as a "general purpose technology" (GPT) as it satisfies the three main features that an innovation should have for imprinting a widespread and relevant effect across the whole of society: pervasiveness, innovation spawning and scope for improvement [33]. Pervasiveness captures the potential applicability of an innovation in several areas of production; innovation spawning reflects the existence of complementarities among several actors in different technological areas; and scope of improvement implies the existence of an efficiency level in the adoption of the technology over time. Also, Rothaermel and Thursby [70] see nanotechnology "as a scientific field with great technological opportunity and economic potential, with the hopes especially high for breakthroughs and advances in medicine, manufacturing, high-performance materials, information technology, and energy and environmental technologies". Nanotechnology is also defined as a science-reality which is being used to revolutionize the products we buy, the ways in which they are manufactured and our approaches to addressing global challenges [85]. Also, the importance and diverse nature of this field are also documented by the numerous "nano journals" indexed by the Science Citation Index that include the prefix nano in their title. Finally, huge public investment has been directed towards nanotechnology to support scientific and technological researches through its National Nanotechnology Initiative, the USA has invested $3.7 billion, the European Union has invested $1.2 billion and Japan $750 million (The Daily Star 2012), and specific technological and industrial platforms and infrastructures have been created in this area [51]. The early 2000s saw an increasing public awareness of nanotechnology and the beginnings of commercial applications based on nanotechnology, promoted both by newly established start-ups and large firms which significantly invested in this area.

3.2. Identifying nanotechnology patents

Although nanotechnology is still at an early stage of development and its full market potential will be disclosed in future years, there has been a real "boom" in the number of nanotechnology patents registered all over the world, starting in the 2000s [42,69]. According to the Wall Street Journal (2004), "[P]atents awarded annually for nanotechnology inventions have tripled since 1996, with 10-fold or greater increases in some areas during the past three years". However, providing a clear definition of what constitutes a nanotechnology patent is not an easy task, given the many different scientific and technical fields involved, which make it difficult to adopt conventional International Patent Classification (IPC) classes.

In order to facilitate interdisciplinary searches and monitor trends in nanotechnology, different approaches have been developed in the literature to identify nanotechnology patents [6,24,37,65,93]. The first method relies on specific nanotechnology patent classes and cross-referencing categorizations which have been introduced by patent authorities, such as the International Patent Class B82, the Japanese Patent Office (JPO) Class ZNM, the US Patent and Trademark Office (USPTO) Class 977 and the European Patent Office (EPO) Class Y01N. The second method relies on the application of keyword systems based on a search for one or more specified words or phrases in the available text of the patent documents. Some initial approaches searched for "nanotechnology", "nano" and similar terms. More sophisticated approaches based on keywords, instead, identify and refer to topics and technologies related to the nanoscale such as "monolayer", "quantum dot" and similar terms. Although a certain level of overlap exists among these methods, they provide different results for the categorization of patents as nanotechnology-related.

Over the last few years, several academic studies related to nanotechnology have been conducted by adopting the abovementioned methods to identify nanotech patents. Some works have applied the technological classification provided by the different national patent offices (i.e., [70,73,75]), others have used keyword searches (i.e., [6,37,65]). Finally, few works have tried to adopt a more comprehensive perspective by integrating and comparing several methods with each other (i.e., [24,93]).

In this paper, we decided to refer to the method based on the search of nano-related keywords, since it is the most broadly used in the literature [6,24,65,93], and we decided to adopt the classification developed by Zucker et al. [93]. This choice allows us to exploit data from a recent and exhaustive database on US patents in nanotechnology, which will be presented later in detail in the next section dedicated to the description of our sample.

4. Data and methods

4.1. The sample

To perform our analyses we identified all the patents granted at the United States Patent and Trademark Office (USPTO) in the field of nanotechnology over the period 1976–2005 through the COMETS database (Connecting Outcome Measures in Entrepreneurship Technology and Science, also known as STARS database, the Science and Technology Agents of Revolution). COMETS is a public database sponsored by the Ewing Marion Kauffman Foundation and the Science of Science and Innovation Policy (SciSIP) Program at the National Science Foundation.[4] The COMETS database includes information on 3,911,924 US patents in all science and technology areas (S&Ts), with grant dates through to 2010. However, flags used to identify nanopatents are available only for patents with grant dates from 1976 to 2005, corresponding to 3,035,112 observations. The COMETS classification of a patent as nanotechnology-relevant or not is based on one of the following methods: (1) a search for nano-related keywords, (2) two probabilistic analyses of text (with all nanosubfields considered simultaneously or separately), (3) by referring to the US Patent Classification 977 (Nanotechnology) or (4) through any of these four approaches.

In the keyword methods, keywords were any term that was prefixed with “nano” and (A) the 140 most commonly occurring noun phrases in the Virtual Journal of Nanoscale Science & Technology (VJN), (B) 297 “glossary” terms primarily derived from recommended search lists received from collaborators and advisory board members who are specialists in the field and supplemented by a web search of nanotechnology glossaries, (C) with the exception of pure measurement terms.[5] This method has the disadvantage of being less effective for early patents, where some search terms were not in common use, and for recent patents, which present very new terms that cannot be included among the keywords. However, this approach provides a comprehensive picture of the “nano”-ness as it deeply analyzes the full content of the patent through preselected keywords.

The probabilistic method is a relative frequency method that ranks the patent documents in order of relevance to a set of query terms that are not preselected, but vary depending on the content of the document. For this reason it considers more patents as nanotechnology-related than the previous method. However, too broad a definition would make any result meaningless as any small technology would be labeled “nano”.

Finally, the method based on the identification of nano-relevant patents by an outside authoritative source (i.e., the classifications provided by the US Patent and Trademark Office) is the most restrictive approach. However, also choosing too restrictive a definition might not be the right choice, as it would leave essential technologies outside of the nanotechnology area.

Given the advantages and disadvantages of each approach, we decided to rely on the first method as it is the most broadly used in the literature [6,24,37,65,93] and provides the most comprehensive picture of the existence of nano-related patents. Our final sample, thus, includes 58,244 US patents identified in the COMETS database as related to nanotechnology according to the approach based on keywords. For each patent, we used the COMETS database in order to collect information on application and grant dates, applicants, IPC classes, number of claims and forward and backward citations. Similar information was collected for all the S&T patents included in the COMTES database (for a total of 3,911,924 US patents), in order to compute time- and sector-adjusted patent indicators, as described in Section 4.2.

4.2. Variables

4.2.1. Dependent variables

Our dependent variable is patent scope. Ideally, patent scope should be measured through the subjective assessment of experts in the nanotechnology fields (i.e. researchers, patent attorneys) in order to value in detail the breadth of claims included in the patent. However, this is practically impossible for large groups of patents. We thus decided to apply a different measure of patent scope, based on the number of claims included in each patent (Num_Claims). Claims in the patent specification delineate the property rights protected by the patent. As a consequence, in the economic literature, the number of claims has been extensively used as a measure of breadth or legal scope of protection since a more subject matter is included ([39,52,71,81] and Jaffe 2000). According to this dominant view in the literature, a broader patent scope (assessed in terms of numbers of claims) implies a higher level of generalization.[6] This measure has already been associated with patent scope in the literature [81,43,87]. However, as “raw counts of claims depend heavily on technology-specific practices and their evolution over time” ([88]: 542), we also constructed a second time- and sector-adjusted indicator of patent scope (Num_Claims_Rel). Following van Zeebroeck and van Pottelsberghe de la Potterie [88], we computed this normalized indicator for each patent by deflating our precedent variable by the median number of

[4] It is possible to refer to the NBER paper by Zucker et al. [93] for a detailed description of the contents, methodology and use of the public online COMETS database. Details of the database are also available at the website www.kauffman.org/comets.

[5] A complete list of all nano-related keywords used in the COMETS database is provided in Table 2 of the paper by Zucker and Darby [94].

[6] We follow this interpretation, as it represents the dominant view in the literature [81,43,87] and it is also confirmed by practitioners. However, we are aware that the breadth of a patent can be tied to the formulation of the claims, and, in certain cases, adding claims could even result in narrower filing [87].

claims contained in patents with the same technological field (as defined by the primary 4-digit IPC class) and the same year of application. The normalized indicator is thus computed as follows:

$$\mathrm{Num\_Claims\_Rel}_i = \frac{C_i}{\mathrm{median}_{T_i,\ Y_i}\ C_j}$$

where Ci is the number of claims of the patent application i and (Ti, Yi) is the set of applications filed in the same technological field (Ti) and year (Yi) as patent application i.

4.2.2. Independent variables

As our main goal is to assess whether and how patent scope varies over time as an emerging technology develops and matures, we created four dummies to identify different phases in the development of the nanotechnology field. As previously mentioned, it is not an easy task defining a precise evolution of this technological area. However, some studies have tried to describe its development in a systematic manner [6,26,35,48]. In this paper, we refer to the work by Grodal [26] that identified three main phases of development of nanotechnology (mobilization, legitimization and institutionalization), depending on the level of involvement of the communities that played an important role in the field (futurists, government, service providers, companies and science). The period 1984–1995 is defined as the mobilization phase, characterized by the involvement of only the futurist group. The period 1996–1999 is defined as the legitimization phase where also the government and service providers started to enter into the nanotechnology area. Finally, the period 2000–2005 corresponds to the institutionalization phase, characterized by industrial firms and scientists also adopting the nanotechnology label. In addition to the classification provided by Grodal [26], we also introduced an incubation phase, which includes nano-related patents with application years ranging from 1976 to 1984.

We also introduced a set of variables related to the patent applicants with the aim of assessing the presence (or absence) of different strategies in the use of patent scope by different types of applicants.[7] In order to identify different types of applicants, we used the dummy variable Firm Applicant taking the value 1 if the main applicant is a firm, and 0 otherwise (i.e., academic institutions such as universities, national laboratories, research institutions, academic scientists or schools, the US government and other organizations or applicants not recorded). Information on the nature of the applicant was collected through the COMETS database.[8]

4.2.3. Control variables

We included a set of control variables that could influence patent scope according to previous literature [45,46,87]. van Zeebroeck et al. [87] showed that patents filed by US applicants were composed of more claims than the average patent filed at the EPO. We therefore included the dummy US_Applicant in order to differentiate between applicants located in the United States (dummy equal to 1) and in the rest of the world (dummy equal to 0). We assessed whether the number of claims varies depending on the number of applicants of each patent (Number of Applicants). Moreover, we introduced the variable Backward Citations as a proxy to measure the novelty and complexity of a patent. We constructed this measure counting the number of citations of previous documents provided in the text of the patent, according to the COMETS database. The number of applicants and the number of backward citations can be used as a proxy of the underlying technical complexity of the patent, which can ultimately impact on patent scope [87]. Finally, Lerner and Merges [46] and van Zeebroeck et al. [87] showed that the average values of patent scope significantly vary across technological fields. Therefore, in order to control for the variation of patent scope across different technological areas, we referred to the work by Zucker and Darby [91], which classifies all patents in five S&T macro-areas (deriving from the concordance between different science and engineering areas, technological areas and industrial applications): Computer Science, Biology/Chemistry, Semiconductor, Other Sciences and Other Engineering Fields. We thus created dummy variables for the first four macro-areas, using the Other Engineering Fields area as the baseline case.

5. Analyses and results

5.1. Descriptive evidence

We initially analyze the more general trends in patenting activity and in the scope of patents over the different phases of the emergence of the nanotechnology field. Fig. 1 shows the overall trend of patenting in nanotechnology from 1976 to 2005. It clearly shows a slow and steady increase in the number of nanotech patents in the first phase of incubation, and a steep acceleration of patenting rates in the mobilization phase, with the year 1986 acting as a turning point for the growth. This is coherent with the history of the field, which sees the publication of the volume Engines of Growth as a key-moment for the popularization of the nanotechnology concept. The pattern of strong growth also continues in the legitimization phase (1996–1999), and the number of nanotech patent filings reaches a peak in the year 2001 with 6553 filings. The rapid decrease in the number of nanotech patent applications in the following 3 years, documented in Fig. 1, should be attributed to a truncation effect due to the grant lag (the period of time between an initial patent application and its final granting), which usually takes several years.[9]

Table 1 presents the summary statistics of our sample of nanotech patents and Table 3 shows the correlation matrix for our main variables. It is possible to notice that the average number of claims for patent (our proxy of patent scope) is 19.14, while the same measure assessed in order to adjust for

[7] To construct our variables containing details of the patent applicants, we only considered the main applicant that is the applicant that appears first in the patent document.

[8] See the paper by Zucker and Darby [94] for the methods adopted in the COMETS database to identify and classify inventors and applicants.

[9] The paper by Popp et al. [63] based on data from the NBER patent dataset shows that, for patents granted in 1996, the last year covered by the study, the average grant lag was around 32 months. Therefore, as suggested by Hall et al. [27] it is advisable to consider at least a 3-year “safety lag” when analyzing patent data based on application dates.

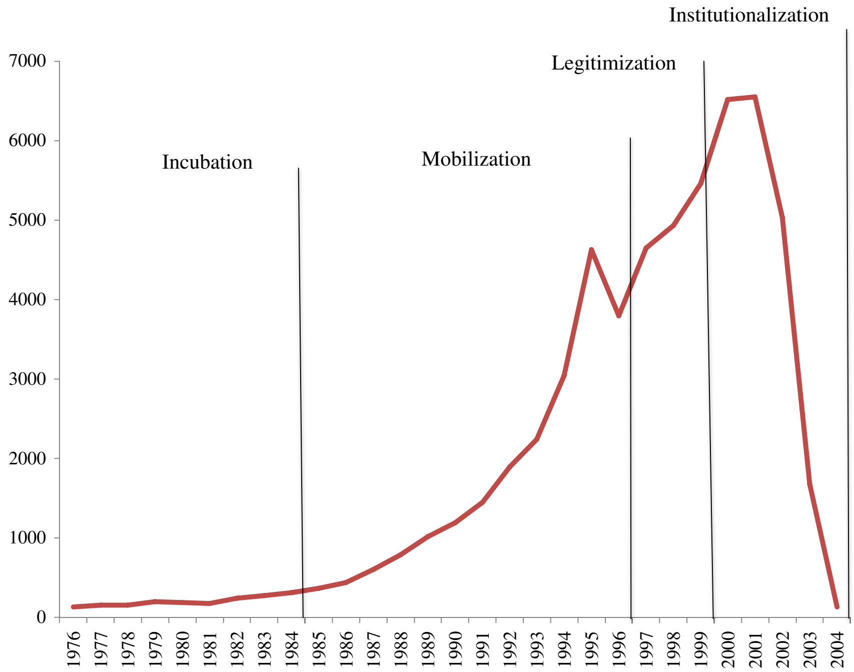

Fig. 1. Nanotechnology patent applications at the USPTO.

time- and sector-factors has a median value of 1.43. As far as the possible technological areas are concerned, 33% of nanotech patents belong to the field of biology and chemistry, while only 7% to computer science. The distribution of the applicants depending on their geographical location is homogeneous between the United States (54%) and the rest of the world (46%), while in terms of affiliation there are greater differences, as 82% of the sample refers to patents held by corporations.

We also performed ANOVA analyses to compare between group differences in our indicators of patent scope (measured both in absolute and in relative terms) to analyze its evolution over the different phases of the emergence of nanotechnology (Table 2).

When we look at absolute values, we see that the number of claims systematically increases over the different phases. Nanotech patents on average had around 14 claims in the incubation phase, 16.36 claims in the mobilization phase, 19.77 claims in the legitimization phase and 21.44 claims in the institutionalization phase. The F-test derived from ANOVA statistically supports (at the 0.01 level) the presence of a significant difference in the means observed in the four periods. This first result is extremely interesting, since it apparently contradicts previous anecdotal and empirical evidence claiming a narrowing of patent scope over a new technology life-cycle [52]. However, based on the arguments discussed in Section 2, we should bear in mind that this result may simply reflect a more general trend towards increasing the number and length of claims in patent applications, which has been well documented by previous research [87]. When we look at the time- and sector-adjusted indicator Num_Claim_Rel, in fact, we notice a completely different picture. The normalized indicator of patent scope now systematically declines over the first three phases of the emergence of nanotechnology (it respectively takes the average values 1.54, 1.44, 1.41 in the incubation, mobilization and legitimization phases) and then slightly increases again in the institutionalization phase, reaching the value of 1.42. Also in this case, the F-test from ANOVA supports the existence of statistically significant difference (at the 0.01 level) between the means. In line with previous explanations, the progressive reduction of patent scope, once time and sector effects are controlled for, can be primarily due to maturation of the technology, which narrowed the opportunities to stake broad claims and increased the risks of infringing previous protected inventions.

Table 1
Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Num_Claims	58,244	19.14	16.98	1	513
Num_Claims_Rel	58,244	1.43	1.25	0.05	32.06
Incubation	58,244	0.03	0.16	0	1
Mobilization	58,244	0.31	0.46	0	1
Legitimization	58,244	0.32	0.47	0	1
Institutionalization	58,244	0.34	0.47	0	1
Computer Science	58,119	0.07	0.25	0	1
Biology/Chemistry	58,119	0.33	0.47	0	1
Semiconductor	58,119	0.16	0.37	0	1
Other Sciences	58,119	0.2	0.4	0	1
Other Engineering Fields	58,119	0.36	0.48	0	1
Number of Applicants	56,198	1.05	0.27	1	13
Backward Citations	53,956	11.57	20.5	1	726
US_Applicant	56,198	0.54	0.5	0	1
Firm_Applicant	56,198	0.82	0.38	0	1

Table 2
ANOVA analyses.

Variable	Statistic	Incubation	Mobilization	Legitimization	Institutionalization	Total	F-test
Num_Claims							
	Mean	13.91	16.35	19.78	21.44	19.14	346.09***
	Std. Dev	11.66	14.75	17.33	18.38	16.98	
	Freq	1519	17,958	18,852	19,915	58,244	
Num_Claims_Rel							
	Mean	1.55	1.44	1.41	1.42	1.43	6.55***
	Std. Dev	1.31	1.29	1.23	1.25	1.25	
	Freq	1519	17,958	18,852	19,915	58,244	

*** $p < 0.01$.
** $p < 0.5$.
* $p < 0.1$.

5.2. Regression results

We then ran regression analyses in order to control for the effects of other influences that might have affected patent scope. Table 4, column 1 reports the results of our negative binomial regression analyses in the case of the number of claims as a dependent variable. As in the paper by van Zeebroeck et al. [87], we decided to employ a negative binomial specification given the count nature and high skewness of our first dependent variable. In order to avoid multi-collinearity problems, we dropped the dummy variable Mobilization in the models, so that the interpretation of results concerning the other three phases of development takes this phase as the baseline case.

In line with previous descriptive evidence, our results show that the scope of nanotech patent applications, measured in terms of absolute number of claims, increases passing from the incubation to the mobilization phase (the dummy incubation has a negative coefficient, statistically significant at the 1% level). Similarly, it also increases in the legitimization and institutionalization phases, as compared to the mobilization phase (both dummies are significantly positive at the 1% confidence level).

In addition to that, our analyses show that patents filed by companies tend to be less broad than the rest of nanotech patents. The coefficient of the dummy Firm_Applicant is indeed significantly negative at the 1% confidence level. Given that the rest of nanotech patents is mainly assigned to universities and other public research centers, it is likely that they rely more on recent science than corporate patents, thus presenting a broader scope of potential applications.

Concerning our control variables, we find a positive and statistically significant effect (at the 1% confidence level) of the variable US_Applicant. In line with previous literature, this suggests that US applicants tend to formulate their claims in more detail than applicants from other countries. Looking at the different macro-sectors, nanotech patents in the fields of biology/chemistry, semiconductors and other sciences tend to be broader than the remaining categories (the three dummies are positive and statistically significant). Similarly to the results of van Zeebroeck et al. [87], patents with a higher number of backward citations tend to have a broader scope (the coefficient is positive and significant at the 1% confidence level), suggesting that more complex patents require more claims to be patented. On the other hand, the number of applicants does not have any statistically significant impact on patent scope.

When we turn to the regression model using the normalized indicator Num_Claims_Rel, however, the evidence we find is different (see Table 4, column 2). In this case, we applied simple OLS regression models, given the continuous nature of the normalized indicator. As previously shown in the descriptive analyses, once we normalize the number of patent claims for time- and sector-effects, we find a reduction of

Table 3
Correlation matrix.

#	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Num_Claims	1														
2	Num_Claims_Rel	0.96	1													
3	Incubation	−0.05	0.02	1												
4	Mobilization	−0.11	0.01	−0.11	1											
5	Legitimization	0.03	−0.01	−0.11	−0.46	1										
6	Institutionalization	0.10	0.00	−0.12	−0.48	−0.50	1									
7	Computer Science	0.00	0.00	0.01	0.00	0.01	0.00	1								
8	Biology/Chemistry	−0.01	0.02	−0.04	0.07	0.02	−0.07	−0.18	1							
9	Semiconductor	0.00	−0.01	−0.05	−0.06	−0.02	0.09	−0.10	−0.29	1						
10	Other Sciences	0.05	0.00	−0.03	0.00	0.01	0.00	−0.10	−0.21	−0.15	1					
11	Other Engineering Fields	−0.01	0.00	0.09	−0.02	−0.02	0.01	−0.14	−0.33	−0.26	−0.27	1				
12	Number of Applicants	−0.01	−0.01	−0.02	0.01	0.01	0.00	−0.02	0.05	−0.01	−0.02	−0.01	1			
13	Backward Citations	0.21	0.17	−0.05	−0.11	0.03	0.09	0.00	0.02	−0.02	0.01	0.01	−0.03	1		
14	US_Applicant	0.14	0.14	0.05	0.02	0.00	−0.04	−0.06	0.17	−0.11	0.00	−0.04	−0.06	0.19	1	
15	Firm_Applicant	−0.01	−0.01	0.03	−0.03	−0.01	0.02	0.08	−0.18	0.06	−0.01	0.08	−0.09	0.06	−0.13	1

patent scope passing from the incubation to the mobilization phase (the dummy incubation is now significantly positive at the 5% confidence level). The reduction further proceeds in the legitimization and in the institutionalization phase (both dummies are now significantly negative at the 1% confidence level).

In this model, moreover, the coefficient of the variable Firm_Applicant remains negative, although not in a statistically significant sense. This suggests that nanotech patents filed by companies are not significantly different from other patents in terms of normalized number of claims. Concerning the control variables, we find that the results are largely in line with the previous model. The dummies US_Applicant, Semiconductors, and Biology/Chemistry remain positive and statistically significant. The dummy Computer Science now becomes statistically significant, but only at the 10% confidence level, whereas the dummy Other Sciences looses it significance level. The number of Backward Citations remains positive and statistically significant at the 1% confidence level.

6. Robustness check

In addition to the previous regressions, we also performed a set of additional analyses as robustness checks by changing, one at a time, three variables in our econometric models: the timing variable, the measure of patent scope and the method to identify nano-tech patents.

First, as the four phases used for describing the nanotechnology life-cycle could constrain the interpretation of our results, we replicated our analyses by using the application year of the patent as an explanatory variable in order to assess the progressive maturation of nanotechnology (instead of the dummies for the different phases). We also performed this test to replicate the approach by Lerner and Merges [46] who used a similar dependent variable in their analyses of patent scope in the biotechnology and software sectors. As shown in Table 5, the results are similar to the previous ones: the absolute measure of patent scope increases over time, while the relative measure decreases. Furthermore, firms tend to have patents with a lower number of claims as compared to other organizations, particularly compared to academic institutions.

Second, instead of measuring the level of patent scope through the number of claims, we followed the alternative method identified and validated by Lerner [45] in his study of the biotechnology industry. We therefore counted the number of IPC classes to which patent examiners assigned each nanotech patent, using the first four IPC digits only. In addition to that, for the measure of patent scope based on the count of the number of claims, we also constructed a normalized indicator, by deflating this measure by the median number of IPC classes contained in patents with the same technological field (at the 4-digit level) and the same year of application. Our findings (not reported in this paper due to space limits) substantially hold even in this case, with the sole exception of the impact of Firm_Applicant, which becomes statistically insignificant at conventional levels.

Table 4
Regression analyses — main models.

Variables	(1) Num_Claims	(2) Num_Claims_Rel
Incubation	−0.169***	0.0868**
	(0.0210)	(0.0355)
Legitimization	0.162***	−0.0593***
	(0.00800)	(0.0137)
Institutionalization	0.225***	−0.0681***
	(0.00788)	(0.0136)
Computer Science	0.0192	0.0434*
	(0.0129)	(0.0222)
Biology/Chemistry	0.0147*	0.0682***
	(0.00775)	(0.0134)
Semiconductor	0.0157*	0.0413***
	(0.00919)	(0.0158)
Other Sciences	0.0848***	0.0156
	(0.00823)	(0.0142)
Number of Applicants	−0.0138	−0.00591
	(0.0123)	(0.0207)
Backward Citations	0.00609***	0.00890***
	(0.000180)	(0.000269)
US_Applicant	0.228***	0.309***
	(0.00658)	(0.0113)
Firm_Applicant	−0.0231***	−0.0220
	(0.00854)	(0.0148)
Constant	2.632***	1.206***
	(0.0176)	(0.0301)
Observations	51,938	51,938
R-squared	–	0.045
LN (alpha)	−0.788***	
LR test of alpha = 0	3.7e + 05***	

Legend — standard errors in parentheses.
*** p < 0.01.
** p < 0.5.
* p < 0.1.

Table 5
Regression analyses — robustness check.

Variables	(1) Num_Claims	(2) Num_Claims_Rel
Application_Year	0.0211***	−0.00944***
	(0.000648)	(0.00111)
Computer Science	0.0189	0.0434*
	(0.0129)	(0.0222)
Biology/Chemistry	0.00657	0.0709***
	(0.00773)	(0.0133)
Semiconductor	0.0116	0.0460***
	(0.00920)	(0.0158)
Other Sciences	0.0838***	0.0161
	(0.00822)	(0.0142)
Number of Applicants	−0.0175	−0.00436
	(0.0123)	(0.0207)
Backward Citations	0.00608***	0.00898***
	(0.000180)	(0.000269)
US_Applicant	0.229***	0.307***
	(0.00658)	(0.0113)
Firm_Applicant	−0.0190**	−0.0246*
	(0.00854)	(0.0148)
Constant	−39.41***	20.01***
	(1.294)	(2.222)
Observations	51,938	51,938
R-squared	–	0.045
LN (alpha)	−0.787***	
LR test of alpha = 0	0.00666	

Legend — standard errors in parentheses.
*** p < 0.01.
** p < 0.5.
* p < 0.1.

Finally, in a different specification, we introduced a different method for identifying nanotech patents. This alternative approach does not rely on the search of nano-related keywords in the text of the patent to identify nanotech patents, but on the class 977 introduced by the USPTO. As discussed in the methodological session, this is the most restrictive approach and, thus, makes it possible to analyze the nanotechnology sector from a narrow point view, by including only patents that are nano-related according to the classification of the authoritative source USPTO. We relied on the classification of the COMETS database to identify a different subset of nanotech patents according to this approach. Also in this case, the results of our regression analyses (not reported here) substantially confirm previous findings.

7. Discussion and conclusions

In this paper, we have analyzed how patent scope evolves in the early stages of an emerging technology, controlling for a series of factors related to timing, sectors of interest, type of applicant and characteristics of the underlying technology. We have also aimed at increasing our understanding of the evolutionary and competitive dynamics of the nanotechnology area, considered as a typical example of an emerging technology. The data we provided as to the patenting trends in the nanotechnology field are consistent with the pattern highlighted by technology life-cycle models [21,30]).

We have assessed the level of nanotech patent scope through two different measures based on the claims contained in the patent document: an absolute measure, representing the total number of claims, and a relative measure, assessed as the number of patent claims deflated by the median number of claims contained in patents with the same technological field (as defined by the primary 4-digit IPC class) and the same year of application. Furthermore, we have analyzed whether the propensity to file broad patents varies according to the nature of the applicants, differentiating corporate patents from other patents (i.e. university and PRO patents).

Our results suggest that the evolution of patent scope over time is different depending on the type of measure considered. Patent scope in absolute values systematically increases along the four different phases of development we have identified (incubation, mobilization, legitimization and institutionalization). However, the relative indicator of patent scope shows a different trend, as it systematically declines over the subsequent phases of development of nanotechnology. This confirms that a pattern of increasing specialization of patents characterized the nanotechnology patent landscape in the period under study, with a narrowing down of the breadth of protection sought by the average patent as the technological trajectory proceeds towards more mature phases. The presence of early broad patents, coupled with the proliferation of later patents that we have documented, can generate a series of critical consequences for the future development of innovation activities in the nanotechnology field. The first issue deals with the emergence of patent thickets on key technologies, as a result of the existence of broad patents covering the building blocks of nanotechnology. The existence of dense webs of overlapping rights on key nanotech elements – such as quantum dots, carbon nanotubes, nanowires and fullerenes – has been indeed recently documented in the scientific literature [29,61]. As a related issue, the potential multiple infringements stemming from the presence of such patent thickets have raised concerns about hindering the development of nanotechnology, because of the time and money required for inventors to acquire all the necessary licenses or avoid lawsuits [61].

Our findings also partially confirm the existence of differences in the breadth of patents depending on the type of applicant. Patents by firms tend to be less broad than patents of other organizations (in particular academic institutions). This result can be explained considering the fact that academic institutions tend to undertake basic research that covers different aspects and functionalities of a technology and, thus, shows, on average, a broader number of potential future applications (and consequently a higher number of claims). Such results thus confirm previous evidence showing a higher degree of originality and generality of university patents as compared to corporate patents [34,72,82], even in the specific case of an emerging technological field such as nanotechnology.

Our findings present clear managerial implications as to the importance of strategically leveraging on patent protection in the early phases of a new technology life-cycle, in order to be better positioned in the "gold rush" for the exploitation of the new technology.[10] On the one hand, in the early days of a nascent technology, companies should be well aware of the future potential applicability of their inventions over different industries and application contexts, and protect it by adequately drafting patent claims. Our findings suggest that early entrants may benefit from pursuing a proprietary patent strategy in an emerging technological area [78]. This requires investing resources to strengthen the quality and breadth of their patent rights in the nascent phase of a new technology, by obtaining well-researched and well-written pioneering patents, complementing them with a series of subsequent complementary inventions, and enforcing them adequately. On the other hand, later entrants should cautiously perform state-of-the-art searches in order to check that freedom to operate exists. Moreover, the construction of a strong and broad patent portfolio could also be strategically leveraged by companies in order to operate in a technological space which can become very rapidly overcrowded by multiple and overlapping patent claims. In this sense, a leveraging patent strategy could also be exploited in the subsequent phases of the technology life-cycle in order to take advantage of broad patents obtained in the early phases, so to generate substantial revenues from licensing deals or establish new strategic alliances. In particular, young and innovative companies could also leverage on a rich and broad intellectual property base to pursue license-based business models, centered on the commercialization of proprietary technologies via licensing,

[10] The strategic use of patent claims in the early phase of a new technological trajectory clearly emerges in the normative indications given by patent attorneys in the novel field of nanotechnology. See, for instance, the following quotes taken from business journals and conference presentations: "Based on the ever changing patent nanotech landscape, companies must strategically stake patent claims or risk missing the nanotech patent gold rush" [16]; "Nanotechnology patents surge as companies vie to stake claim" [66]; "Positioning your IP. Land Grab: territories are not well-defined and need to define your IP as broadly as possible" (Scozzafava, M.R., Nine Zeros Nanotechnology Breakfast Roundtable, February 2007).

without necessarily investing on the complementary resources required to produce and bring into the market new products, components or services [20,49,62]. In addition to royalty revenues from licensing, leveraging strategies centered on a strong and broad patent portfolio can be also exploited to gain other types of benefits over the different phases of a new technology life-cycle. For instance, new ventures can exploit their patent portfolio to attract external funding by venture capital firms, since it is well established that strong and broad patents positively influence not only the likelihood to obtain VC funding, but also the overall valuation of the target company [11,45,57].

Our study also presents important policy implications, in particular for national and international patent authorities, as to the optimal breadth of patent awards in a new technology's formative years. From a policy perspective, understanding in depth the dynamics of patent breadth for emerging technologies is of paramount importance in order to avoid a proliferation of broad patents producing a thicket of conflicting legal claims, which could ultimately slow innovation rates and generate numerous legal disputes [4]. Our results suggest the importance for national patent offices to timely monitor the emergence of a novel technological field and to create early specific technological classes devoted to it in order to facilitate the searching activity by inventors. Moreover, it becomes important to create early on a group of patent examiners with specific expertise in the emerging technology so to effectively perform the examination process. In addition to that, as suggested by the seminal article by Merges and Nelson [52], patent offices and courts should contrast the dangers of awarding overly broad patents early in the history of a science-based industry, by inducing limitations in the scope of pioneering patents based on a close adherence to the inventor's disclosure and a judicious use of the doctrine of equivalents. Finally, in order to avoid the risks of mutual hold-up due to a dense web of overlapping patent rights, particular attention should be given, in the case of new emerging technologies, in monitoring the development of patent thickets and the occurrence of multiple litigation cases. Different solutions have been used in the past, following technological discontinuities, to deal with the emergence of this kind of obstacles for innovation development, such as the formation of patent pools [52] or mechanisms to establish more or less automatic cross-licensing arrangements [53].

Our paper presents some limitations that can be addressed by future research on this topic. First, our analyses only take into consideration the period 1976–2005, due to limits in the classification of nanotech patents in the COMETS database. As nanotechnology is still at an early stage of development and its market potential will be disclosed in the coming years, it could be interesting for future research to extend our analyses to a longer period in order to also include a phase of maturity.

Second, we have only analyzed the evolution of patent scope for the nanotechnology context. However, we are aware that we cannot generalize our findings, as the dynamics of patent scope can be different depending on the science and technology area considered. In particular, nanotechnology is a general purpose technology that shows particular features not shared with other technological domains. It could, thus, be interesting to perform some kind of comparisons between various types of emerging technologies to show differences and peculiarities, and to understand the factors that impact on their evolution.

Third, we have analyzed the type of patent applicant through a dummy variable that distinguishes between business firms versus other organizations, like universities, research institutions and government. However, in order to investigate the strategic use of patent scope undertaken by different actors, it is necessary to take into consideration the heterogeneity of these organizations. Future research could address this limitation by not only studying different types of applicants, but also, within each category, identifying a set of characteristics that can explain different strategic behaviors in their patenting activity.

Fourth, we have resorted to quantitative measures in order to proxy patent scope, using bibliometric indicators such as number of claims or number of IPC classes already validated by previous literature [45,87]. However, patent documents contain lengthy, detailed and technical information, and ideally patent scope should be measured through the subjective assessment of experts in the technical fields in order to value in detail the breadth of claims included in the patent. Although these qualitative data can be difficult to process through standard statistical techniques [31], future research could exploit more advanced approaches in order to undertake this objective. A growing number of studies, for instance, have applied text mining techniques to assist the tasks of patent analysis and patent mapping [18,83]. Another promising line of research that future studies could exploit to this purpose is the application of a rough set theory [61] that represents a mathematical tool for managing vague and uncertain data and drawing conclusions from the data by giving easy explanations of the obtained results. Rough set theory has been already applied in the patent context, for instance in order to analyze existing patent information in a portfolio of patented technologies and derive some rules to better guide resource allocation decisions across technologies [36]. In our context, it could be useful, for instance, to better identify the breadth of a patent and its level of development with respect to an existing technological trajectory, in order to define some rules for predicting its potential and the opportunity to further invest in its development.

Finally, this paper can be considered a preliminary effort for future research to extend our description of the evolution of the nanotechnology sector up to more recent years, by studying performance implications for firms. Indeed, it could be interesting to investigate, for instance, what type of financial and strategic returns can be obtained by companies, depending on the strategic orientation in terms of patent scope.

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