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Assessing the nature of nanotechnology: can we uncover an emerging general purpose technology?

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Abstract Attention has increasingly shifted towards the long-run perspective on technological innovation, which suggests that progress comes in waves, each one originating with a major breakthrough or general purpose technology (GPT). This paper seeks to assess whether nanotechnology is likely to be (or become) a GPT, a characteristic that other researchers have sometimes assumed though not necessarily documented. Based on a survey of existing literature, this paper will explore the extent to which nanotechnology addresses three primary characteristics of a GPT: pervasiveness, innovation spawning, and scope for improvement. The paper draws on patent and patent citation databases to highlight the types of quantitative and qualitative information that would be necessary, and in some instances is still lacking, to characterize fully the nature of nanotechnology.

Keywords Nanotechnology · General purpose technology · Patent analysis

JEL Classifications 0330 · 0300 · 0340

1 Introduction

Whenever a new class of technologies emerges, conjectures are advanced on how likely it is that they will change firms' productivity, household production, consumption patterns, and socio-economic relationships. If a core technology has a

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substantial and pervasive effect across the whole of society, it is often termed a "General Purpose Technology" (GPT). The dissemination of electricity at the turn of the 19th century is often said to have the character of a GPT, with reference made to the long wave of downstream innovations spawned by the electric dynamo that reshaped the functioning of the economy. Similarly, the dissemination of microelectronics in the last quarter of the 20th century has in it the hallmarks of a GPT in that it led to new forms of organizations, new products, and has increased the level of competition in service goods that were traditionally produced and consumed locally.

The question we explore in this paper is whether the family of nanotechnologies has the potential of inducing changes in the economy that are comparable in scope to electricity, information and communications technology (ICT), and others that have been previously documented as major breakthroughs.

We discuss the question by drawing on techniques and ideas from two interrelated streams of research. One line of research has hypothesized that the long-run behavior of the financial market and of macro aggregates are best understood by investigating the conditions that have favored the arrival and the process of dissemination of major technologies. The main idea from this literature is that technological change follows a sequence of events in which a major technological innovation is preceded by a number of smaller inventions that expand the range of applicability of the core technology, the so-called "General Purpose Technology." In this paper we will briefly summarize the main features an innovation should have to be part of the club of GPTs and discuss the prediction of theories that explain the rise and fall of productivity and of firms' value as the outcome of the dissemination of a GPT.

We also draw from a stream of research that describes and characterizes technological developments by means of quantitative data taken from patent datasets. In particular, we propose a comparison of the level of "generality" of nanotechnologies relative of that of ICT (usually considered a GPT) and innovations in the drug industry (not considered a GPT). We suggest that the kind of tests proposed in the literature are not easily applicable to emerging technologies because these tests have been devised for situations in which a considerable amount of historical data has been recorded. Nevertheless, the estimations that we perform seem to suggest that nanotechnology satisfies at least one major feature of a GPT, namely that of generality.

The paper begins with an introduction of the main attributes of a GPT and briefly explains the extent to which the existing literature may be used to test whether nanotechnology has one or more of these attributes. Section 3 shows how macro aggregates are predicted to respond to the arrival and the dissemination of a GPT. Section 4 illustrates strategies that have been used to identify a GPT. Section 5 introduces the Generality Index and estimates it for nanotechnology and two other classes of technologies. A conclusion follows.

2 The GPT concept and nanotechnology

Previous research has suggested that a GPT must have at least three attributes: pervasiveness, an innovation spawning effect, and scope for improvement (Helpman & Trajtenberg, 1994). Pervasiveness is intended to reflect the performance of some function that is vital to the functioning of a large segment of existing or potential products and production systems. Bresnahan and Trajtenberg (1995, p. 4) argue that ‘‘continuous rotary motion’’ and ‘‘binary logic’’ are the pervasive elements of ‘‘steam power’’ and ICT, respectively, each of which is considered a GPT.

A pervasive technology would have relatively little visibility in the functioning of the economy unless it fostered new inventions that directly or indirectly result from the early major invention. For instance, the dynamo led to the invention of both the light bulb and electric motor, and stimulated major innovation in plant and urban design (David, 1990). Similarly, the microchip led to an explosion of imaging technologies, memory devices, and digital technologies.

Helpman and Trajtenberg (1994) suggest that such widespread adoption of a core technology is a consequence of a variety of actors coordinating their beliefs about the promise of the technology. Complementary technologies are developed as long as the various actors involved share beliefs that the GPT is spawning innovations in multiple technological areas. Indeed, widespread market adoption may be a consequence of the settling of beliefs among scientists, entrepreneurs, established businesses, government, and consumers.

It remains a theoretical and empirical question whether the core technology of these ‘‘breakthroughs’’ could be improved substantially. Evidence for the scope of improvement for ICT was cleverly summarized by ‘‘Moore’s Law’’ which predicted that the force of competition would stimulate the semiconductor industry to double the number of transistors per chip every 18–24 months. While the regularity of ‘‘Moore’s Law’’ has been observed, it is not clear whether its regularity results from technological factors or from industry coordination around a smooth and predicable trajectory with clear transaction-cost benefits.

Theory suggests that all three aspects will be present in the true breakthrough technologies, those most widely used by firms and households. The mere fact that an innovation can be applied in several areas of production (pervasiveness) does not mean that it will be used. In order for society to employ the technology pervasively, its adoption must be convenient from a cost-consideration point of view, that is, it must reach a certain level of efficiency (scope for improvement), and it must lead to the development of new ‘‘secondary’’ or ‘‘complementary’’ technologies (innovation spawning). Some authors add a fourth element to the definition of a GPT, that of wide dissemination (Lipsey, Bekar, & Carlaw, 1998), although this element is often considered a logical consequence of the other three attributes.

Are there indications that these three basic GPT attributes might be present in nanotechnology? Can we say that nanotechnology performs (or will perform) a generic function, whose efficiency will be greatly improved over time, perhaps as much as that of the microprocessor, and that it stimulates the appearance of new kinds equipment comparable to the modem, or memory storage devices?

With a new technology it is hard to conjecture what aspect of it, if any, will perform a generic function. Although most scholars who are engaged in nanoscience agree that nanotechnology is very small in scale, (in the range of 1–100 nanometers (nm), with one nanometer equaling one billionth of a meter), only a few seem to embrace the notion that if a technology is small in scale it should be considered nanotechnology. From the perspective of this analysis such a change in scale could be paralleled to a generic function, notwithstanding the disagreements among nano-scientists. This would be the case, for instance, if a new scientific principle or a new methodology allows a significant drop in scale that leads to a radical transformation in the range of inputs used in production.

For instance, many industries have voiced concerns over the limits to ''Moore's Law,'' recognizing that any stop to the exponential growth of computing capability would have economic consequences (Harriott, 2000). Nanotechnology, however, has the potential to sustain circuit density increases through small scale lithography alternatives, such as nanoimprint lithography, or eventually self-assembly (Arnold, 1995). Moreover, matter at the nanoscale has been shown to exhibit novel properties that cannot be projected from larger or smaller scales (Kostoff et al., 2006; Tannenbaum, 2005). These novel behaviors, and the human skills to manipulate and engineer them, could form the basis for future pervasive applications.

The GPT characteristic of ''innovation spawning'' may be embodied in evidence of a nanotechnology-oriented value chain of initial, intermediate, and downstream innovations. Lux Research (2006) identifies one such nano-value chain, consisting of an initial set of nanomaterials (such as carbon nanotubes), employed by market intermediaries to create coatings that enhance properties of finishes. The final products then integrate these coatings into a diverse set of products (which may include automobiles, airplanes, electronics displays, nano-treated clothes, refrigerator surfaces with microorganism growth inhibitors, and self-cleaning windows that oxidize organic matter, among others). Lux Research suggests that this nano-value chain is supported by a set of tools including scanning probe microscopes, nanofabrication tools, and computer modeling systems (See also Meyer, 2006 for an alternative perspective on the nano-value chain).

Figure 1 presents a schematic, sequencing both science and commercial technologies. The sequence begins with scientific and technological discoveries in instruments (such as scanning tunneling microscopes or STM and atomic force microscopes or AFM) and nanomaterials (such as buckminsterfullerenes and carbon nanotubes), forming the basis for a value chain. Intermediate and complementary-goods producers are offered, including nanocoatings and composites manufacturers, nano-core processing and memory. The end of the value chain shows a broad range of end-use goods. The figure shows that the boundaries between positions in the value chain overlap.

It is fair to assume that the development of a complete value chain will more likely follow a coordination of beliefs. In nanotechnology, this coordination of

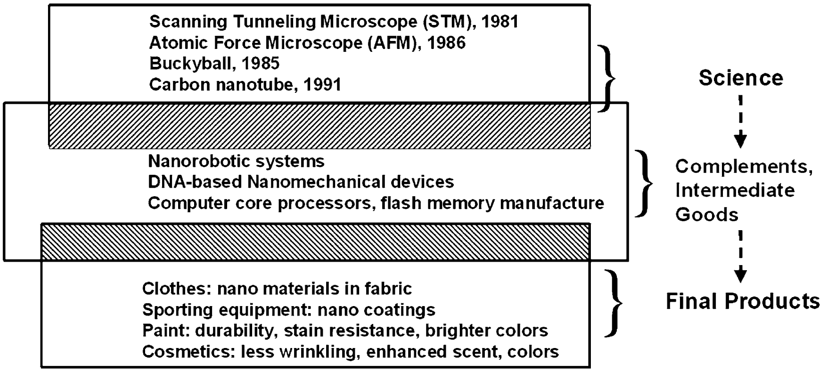

Fig. 1 Potential sequence of science, intermediate goods, and final products in nanotechnology

beliefs appears to be taking hold. Evidence of coordination in science includes Richard Feynman's legendary talk at the American Physical Society's annual meeting in December 1959 ("There's Plenty of Room at the Bottom"), Eric Drexler's *Engines of Creation* (1986) and subsequent formation of The Foresight Institute, the launch of *Nanotechnology* by the Institute of Physics as a multidisciplinary science and engineering journal in 1990, the creation of the Feynman Prize first awarded in 1993 to recognize eminent research in nanotechnology, and the notion that advances at the nanoscale are situated in a convergence of disciplines (Roco & Bainbridge, 2003).[1]

Coordination in the public and private sector may be inferred from the introduction of specific nanotechnology patent classes and cross-referencing categorizations: International Patent Class B82, the Japanese Patent and Trade Office (PTO) Class ZNM, the US Patent and Trademark Office (USPTO) Class 977, and the European Patent Office Class Y01N. In addition, there are multiple professional associations (e.g., NanoBusiness Alliance) and trade magazines (e.g., *Small Times*) dedicated to nanotechnology. Significant coordination of consumer beliefs may be decades away from occurring, although several references to nanotechnology are evident in popular press and public policy documents. For instance, popular media such as Michael Crichton's *Prey* (2002) has portrayed risks from nanotechnology, while public policy has responded with legislation. In 2003, the US Congress enacted The 21st Century Nanotechnology Research and Development Act (Public Law 108-153) which includes specific mention of societal concerns. This statutory mandate has been followed by the NSF's allocation of resources to create a network of science museums and research centers to help educate the public about nanotechnology and social change (NSF, 2005).

Scope for improvement in the family of nanotechnologies may lie in reductions in size, lower costs, and greater complexity. Although nanotechnology is still at a relatively early stage, advances have occurred in semiconductor manufacturing technology (advancing from 90 nm to 45 nm during 2005–2007) (Kanellos, 2005, 2006), and in instrument costs (Atomic Force Microscopes can be obtained at lower prices and/or with greater availability of features at existing prices) (Lux Research, 2006). It is also expected that the field of nanotechnology will like ICT evolve in terms of complexity, with Roco (2004, 2005) suggesting that nanotechnology will undergo four generations of development over the next 20 years.

Armed with such information, several researchers have proposed that nanotechnology is a GPT. Huang et al. (2003) demonstrate through patent analysis that nanotechnology covers a wide range of classes, although Porter, Shapira, and Youtie (2006) criticize the use of an overly broad definition. Moreover, Shea (2005) suggests that nanotechnology is a GPT because it is likely a disruptive and radical technology, but the author's approach does not specifically address the concepts of pervasiveness, innovation spawning, and scope for improvement. While Palmberg and Nikulainen (2006) do examine whether nanotechnology exhibits these three characteristics of a GPT, they do not apply methods commonly used to test for them.

Counting the number of patents by year (showing increases over time) or patents by patent classification (showing increasing diversity) are commonly used to claim

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[1] The disciplinary convergence hypothesis is not without its detractors (See for example, Khushf, 2004).

that nanotechnology is a GPT. However, such information may not in and of itself be adequate to make any such determination. Hall and Trajtenberg (2004), for instance, find that GPT's (as measured by patent citations) do not necessarily have disproportionately higher growth rates in terms of newly issued patents. Moreover, they argue that some patent classifications tend to be more broad-based than others, particularly chemical-related classifications. They suggest that patent classes by themselves do not provide sufficient substantiation of breadth and pervasiveness of a candidate GPT.

3 Why GPT's are important

In the rest of this paper, we explore the gap between studies like Palmberg and Nikulainen (2006), which have claimed that nanotechnology is a GPT, and Hall and Trajtenberg (2004), which find that there are problems with using "counting" methodologies. In so doing, we first find it necessary to justify the assessment of whether a technology is a GPT. We see three chief reasons for engaging in this exercise, contending that there is value to understanding (1) the returns to effective government innovation policy; (2) the technological drivers of economic growth; and (3) the manner in which society could most effectively prepare for these broad technological changes.

3.1 R&D policy

An effective R&D policy would have in it some element of "spurring innovation." It is commonly believed that measures aimed at making intellectual property rights stronger, or inventors' appropriability of the social surplus generated by inventions greater, tend to alter the supply of innovation, without regard to missed opportunities for diffusion. In the GPT theory, the improvement of the core technology goes hand in hand with the range of applications it stimulates in various sectors of the economy. The lower the price of capital embodying complementary technologies—which facilitate the dissemination of the core technology—the wider the range of adoption, and the brighter the prospects of returns on R&D investments directed at improving and expanding the scope of the GPT (Brenhan & Trajtenberg, 1995). However, this argument does not hold in a context in which innovations are unrelated to each other—as it is assumed by most growth theories (Aghion & Howitt, 1992; Romer, 1990). In such circumstances, any positive spillovers—going from the inventors to the users—are detrimental to the innovation rate.

It is not difficult to find cases suggesting that improvements in a GPT are associated, to some extent, with the level of appropriability (i.e., how easily the profits from innovations can be captured). In the semiconductor industry, the level of appropriability is considered low in comparison to other industries, and yet the industry has exhibited spectacular improvements in both invention and economic growth (Irwin & Klenow, 1994). Clearly, the diffusion of information technologies in many economic sectors has been facilitated by the steep decline in the production cost of the microchip. Therefore, if a technology is a GPT it may be more efficient to resolve the classical tension between creating monetary incentives for innovators and fostering the diffusion of innovation by opting for a relatively high level of externalities.

3.2 Economic change

The second reason for investigating the nature of a technology is that any such analysis provides insight into the source of economic expansions or slowdowns. In the United States, the economy experienced sustained high-output growth during the 1960s, while from the early 1970s to the early 1980s output growth was low relative to the post-WWII average. Since the mid-1990s there has been, for the most part, a return to strong growth. Helpman and Trajtenberg (1994) argue that these patterns are associated with the diffusion of GPTs.

When considering economic growth, one view suggests that the appearance of a GPT is followed by two distinct phases. In the first phase, resources are diverted from existing production activity to the creation of new technologies complementary to the GPT. This redeployment of resources from one sector to the other would cause wage and labor productivity rates to stagnate or even decline. This phase is often called the ‘‘time to sow,’’ for the economy is developing technologies that are unproductive in the short-run either because they are not yet efficient or because adopters do not possess the necessary skills and knowledge to use them efficiently. This period of economic slowdown may persist.

It has been argued that the productivity slowdown that lasted for almost 25 years (starting sometime in the first half of the 1970s in the US and other advanced countries) was partly due to the spread of computers. The introduction of computers would have rendered obsolete existing skills and would have caused the abandonment of existing routines. This view sees the slowdown of productivity as the cost the economy suffered to modernize production and upgrade the types of skills needed in the ‘‘New Economy.’’ Paul David (1990) draws a parallel between the diffusion of electricity and computers, arguing that in both cases there was a long delay between the introduction of the GPT and the corresponding productivity surge. It is natural to pose a similar parallel between ICT and nanotechnology, and we explore such a relationship below.

3.3 Societal synchronization

To the extent that a GPT can produce economic benefits, and it requires a high level of synchronization in society, the identifying of a GPT may be beneficial in allowing society to plan for a higher level of needed synchronization. Under the theory of GPTs, coordination between inventors’ and users’ expectations about the usefulness of the emerging technology is considered vital. Improvements in the GPT requires R&D investments, which will likely be made only if the investors expect the development of new complementary technologies or the refinement of existing technology in downstream sectors. In turn, complementary technologies will emerge only if inventors are optimistic about the prospect that the GPT will be widely adopted.

Helpman and Trajtenberg (1994) developed a formal framework showing the dynamic links between the core and complementary technologies. One important aspect that emerges from their analysis is that at any given point in time, researchers must decide whether to devote resources to developing complementary technologies associated with an existing technology, or to a new GPT. The choice depends not only on what happened in the past but also on expectations about the future. The decision is also affected by the past, because a new complementary technology is more productive in an economy in which a wide range of other complementary technologies have been developed.

For these reasons, an incumbent GPT has advantages over a new one. The conjecture is that although a new GPT is more productive when it is combined with the same number of technologies that complement an existing GPT, it is nevertheless not as productive when the range of new complementary technologies is small. If investors believe that at a certain point a large number of complementary technologies associated with the new GPT are forthcoming, then it is more likely that these technologies will be developed. Otherwise, the economy may become trapped in an equilibrium where the new GPT is never adopted and the few firms who ventured to invest in it will fail.

4 Strategies to identify a GPT

In the foregoing, we have (1) suggested that identifying whether a technology is a GPT is a valuable exercise, and (2) cataloged other studies finding that nanotechnology exhibits the characteristics of a GPT. In this section, we identify what we believe is a more systematic approach, one that has been undertaken in recent years by empirical scholars and economic historians in assessing whether a technology is a GPT, and apply it to nanotechnology. The objective of this discussion is to both examine whether nanotechnology "holds up" as a GPT, and also to identify tools that may be used to test other emerging technologies.

Jovanovic and Rousseau (2005) propose new ways to use historical evidence to test for the existence of "scope for improvement," "wide range of use," and the likelihood of spawning complementary innovations. They capture a technology's scope for improvement by analyzing the decline of equipment prices (finding that this decline was greater for ICT than for electricity). The authors suggest that "wide range of use" (pervasiveness) can be analyzed, in their case by comparing the amount of electric power as a percentage the total horsepower in several manufacturing sectors with an estimate of the percentage of ICT investments across the same sectors. Electricity exhibited dissemination across a broader range of industries than did ICT over a comparable time period.

The authors also examine the likelihood that a technology will spawn complementary innovations by using patent analysis. They rely on a notion that patents presage investment in new technologies, representing the rise in initial public offerings (IPOs) and the subsequent change in the structure of capital in favor of new technologies. The authors find "innovation spawning" in the surge of IPO activity that followed the introduction of both electricity and information technologies.

Hall and Trajtenberg (2004) and Moser and Nicholas (2004) venture beyond a simple tally of the number of patents to contend that the data can reveal much more on the question of whether a technological development is a GPT. Instead of measuring the pervasiveness of a GPT by looking at how a new technology affects the composition of capital across sectors, these authors look at the extent to which patents associated with a GPT are cited outside the technology area or industry in which the GPT originated. To address the diffusion delay, which has been associated with a prolonged productivity slowdown followed by an acceleration of productivity, this literature measures the citation lags (the amount of time between the issue of a focal patent and the issue of a future patent that cites back to it), which they contend should be longer for GPTs than for incremental technologies. These authors measure the ‘‘scope for improvement’’ not as a reduction in production cost, but instead with the number of citations within the technological area to which the GPT belongs. An interesting question that the patent literature addresses is the date of arrival of a GPT. Historians often pick a specific event, usually identified with a major investment (e.g., for electricity it has been identified as the construction of a hydro-electric facility at Niagara Falls, New York). Macroeconomists tend to consider an arbitrary threshold in the data, for instance investments in the new technologies rising above a certain percentage of overall investment. In contrast, the patent literature utilizes an ‘‘Originality’’ measure, which allows for a determination of the date of arrival of influential innovations based on forward citations.

Does the patent approach lead to the same conclusions as the macro approach? Moser and Nicholas contend that in the case of electricity it does not. These authors find that patented inventions associated with electricity filed in the 1920s were not as ‘‘pervasive’’ as were chemical and mechanical inventions, because these latter inventions were cited by later patents outside their technological areas more often than were electricity inventions. Moreover, chemical and mechanical inventions were cited more often in general, indicating to the authors a stronger propensity to spur innovation.

These differing conclusions may stem from chemicals and mechanical industries being more ‘‘science-based’’ than was electricity. This observation is an important warning for all nanotechnology investigations that rely exclusively on patents data. There is a risk that the traditional test developed by Hall and Trajtenberg (2004) may be biased in the sense that a science-based technology is more likely to be designated as a GPT, even when such a determination is a spurious result, and not borne out by a judgment made after considering the economic effects that it actually generates.

5 Evidence from patent data

By and large, employing patent data to uncover evidence of a ‘‘general purpose technology’’ is a problematical exercise when studying emerging technologies. Patent data, by its nature, offers information about the current state of a technology, and more commonly about the past development of that technology. Because new technologies are in the process of emerging, the patent characteristics that have traditionally been collected are either not available, or numbers are rather small and thus prone to statistical error. So, empirical research studying whether technologies are or were GPTs has been undertaken only after the technology has matured sufficiently so as to allow researchers to collect an adequate body of information from the patent record (Hall & Trajtenberg, 2004 (ICT); Moser & Nicholas, 2004 (electricity)).

Because nanotechnology is an emerging technology, we are faced with the same limitations. To demonstrate the embryonic nature of this technology area, we

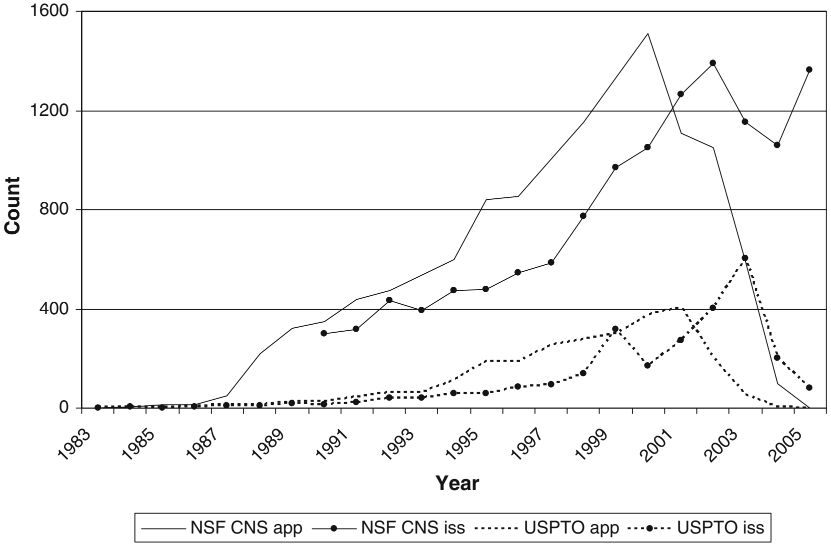

Fig. 2 US nanotechnology patents, 1983–2005. *Note*: NSF CNS nanotechnology patents selected according to a keyword list generated at Georgia Tech in cooperation with the CNS at Arizona State University. USPTO nanotechnology patents selected according to US Patent and Trademark Office classifications. "iss" denotes patents graphed according to issue date. "app" denotes patents graphed according to application year, and thus the seeming decline in applications is not a "true" decline but instead a consequence of truncation because the data source is "issued" patents

present data on the patenting of nanotechnology inventions 1983–2005 (Fig. 2). Four trends of granted patents are plotted in Fig. 2, based on two different definitions of "nanotechnology" patents.[2] One definition is derived from the classification system used at the USPTO, while another is based upon the "keyword" system built by the CNS-ASU team (Porter et al., 2006). Note that the latter definition produces substantially more "US nanotechnology patents" during the 1983–2005 period (12,553 NSF-CNS patents versus 2,639 USTPO-defined patents). Figure 2 presents alternative counts within each definition, measuring each patent both in its year of application and grant.

The time trends demonstrate that nanotechnology has been a slowly growing technology space. Significant application activity did not begin until the late 1980s (under either definition), with relatively small numbers of patents being issued until the 1990s. This relative paucity in the patent record is particularly problematic for the uncovering of GPTs since the primary measurement of this characteristic of technologies has been made with large numbers of patents, using the patents' "forward citation" stream.

All patent applicants are required by law to disclose the prior art (patents and non-patents) upon which the instant invention builds. Following some give-and-take with the patent office (Graham, 2006), and after the patent examiner has had an

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[2] These plots are subject to substantial right-side truncation due to the data being collected from the granted patents—these figures do not include information available in the US since 2001 on published applications.

opportunity to add some references (Alcacer and Gittleman, 2006), the patent issues with a list of patent "backward citations" to prior art. Researchers have used these "backward citations" by looking to patents that issue in the future, and which cite back to the focal patent, to measure the "pervasiveness" of the technology.

Hall and Trajtenberg (2004) suggest using these so-called "forward citations" in uncovering GPTs by employing the Herfindahl–Hirschman Index (HHI) of the patent classes assigned to the focal patent's "forward citations." The resulting measure of "pervasiveness" is termed a patent's "Generality Index" and is defined by the formula

$$\text{Generality} \equiv G_i = 1 - \sum_{j}^{n_i} S_{ij}^2$$

where S_{ij} = share of patent i's forward citations in class j. The theory behind using this measure is that it captures information on the extent to which the focal patent is being applied in a wide range of technologies—the so called "pervasiveness" of a patent. As a patent's "Generality" score approaches 1.0, we know that the patent is being "cited to" by patents in a broader set of classifications, and thus we can infer that the patent is being applied more broadly in distant applications.

If we examine the "Generality" scores across all patents in a particular technology—in nanotechnology for instance—and compare these against the scores for patents in other technologies, we may infer something about the "pervasiveness" of the technology's application throughout the economy. Obviously, any measure built in this way will be very sensitive to right truncation. In the study of new and embryonic technologies in which the patent record is slowly developing, the absence of a sufficient "forward" time window will pose great difficulties in calculating a useful "Generality Index" for individual patents, and thus entire patented technologies.

The trends depicted in Fig. 2 demonstrate that, in the emerging nanotechnologies, substantial numbers of patents began to issue from the USPTO in the 1990s, thus giving us a sufficiently long "forward window" to develop credible "Generality" scores on the earliest patents issued in this new technology space. We present these data below with one important caveat: These generality scores are only representative to the extent that these early patents, and their characteristics, are representative of later patents issued in this emerging technology area.

Table 1 reports generality scores for "nanotechnology" patents as defined by the NSF-CNS "keyword" method, and compares these with scores for "drug" and "computer" patents defined by international patent classifications (Graham, 2006). Scores are reported for the index built from three different measures of patent forward citation breadth: US patent classifications, International patent classifications, and NBER patent-database aggregated technology classes (Hall, Jaffe, & Trajtenberg, 2001). Generality scores for 1990–1993 irrespective of classification scheme demonstrate that the "nanotechnology" patents are more general than drugs patents issued in the relevant year, and compare favorably with, and indeed are higher at every reading than, computer patents. Computer patents are representative of ICT, a technology that we previously mentioned has been found to be a GPT (Hall & Trajtenberg, 2004).

Table 1 Comparison of "Generality Index" scores across three technologies, 1990–1993

	Nanotechnology			Drugs		Computers	
	Variable	Count	Mean	Count	Mean	Count	Mean
1990	Gen US	287	0.620	2188	0.386	1961	0.612
	Gen IC	287	0.642	2187	0.385	1961	0.443
	Gen TC	287	0.540	2187	0.273	1961	0.424
1991	Gen US	293	0.623	2405	0.394	2306	0.610
	Gen IC	293	0.617	2405	0.389	2306	0.445
	Gen TC	293	0.507	2405	0.278	2306	0.431
1992	Gen US	411	0.596	2349	0.387	1956	0.612
	Gen IC	411	0.582	2349	0.388	1956	0.405
	Gen TC	411	0.487	2349	0.268	1956	0.417
1993	Gen US	364	0.608	2499	0.380	2999	0.609
	Gen IC	364	0.605	2498	0.376	2999	0.398
	Gen TC	364	0.511	2498	0.264	2999	0.423

Variable definition: Gen US = Generality based on USPTO-classes; Gen IC = Generality based on International Patent Classes; Gen TC = Generality based upon NBER patent database technology classes (Hall et al., 2001).

These scores on early nanotechnology patents provide us with limited evidence that nanotechnology exhibits the "pervasiveness" characteristic of a GPT. As mentioned previously, conventional measurement techniques for assessing the existence of a GPT require sufficient time to elapse to allow for "forward citations" to develop in the patent record. So, are researchers at an impasse as regards nanotechnology—is the evidence of GPT "pervasiveness" hidden in the latent nature of patent information?

Not necessarily. If ICT is a guide, then it is possible to determine whether this technology, in its early development, also showed associated patents with significantly higher generality scores. And indeed, in 1975–1979, patents designated in primary international class G06F, a class broadly representative of computer software technologies (Graham & Mowery, 2003) showed relatively high generality scores as compared to all other patents.[3] Thus, for this GPT, the patents that appeared early in the technological trajectory demonstrated this measure of "pervasiveness" and thus we can take some confidence in our "nanotechnology" patents showing the same characteristic.

But, as outlined above, a GPT is not characterized by "pervasiveness" alone. Can the patent record help us in determining whether nanotechnology—and indeed, any candidate GPT—exhibits evidence of "coordination of beliefs" among actors or a "sequential" development of complementary technologies? We theorize here that the patent record may contain information that could help in uncovering these two characteristics of GPTs.

As regards "coordination of belief," the key insight behind this characteristic of a GPT is that different actors in society are "conforming" to a set of beliefs concerning the wide applicability of the technology. The set of actors needed to coordinate are necessarily broad, but include at least marketplace actors (such as

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[3] These scores (built from USPTO classes) for computer patents 1975–1979 were 0.63, 0.65, 0.66, 0.68, and 0.67, respectively, and are significantly higher than the scores for all patenting in those years (0.49 in each year).

entrepreneurs) and government actors. Since 2001, the patent record has contained information concerning the identity of the actor who included the citation in the patent references: the inventor (and the inventor's attorney agent), or the patent office examiner (Alcacer & Gittleman, 2006). While the use of these data would entail care due to possible endogeneity (the idea that information is flowing between the parties that leads to the citation placement),[4] nevertheless to the extent that the generality measure is built from the citation record, and that citation record can be tested to determine whether both marketplace actors (inventors) and government actors (examiners) concur about the "pervasiveness" of a technology, it may prove fruitful to use these records as an indicator of "coordination of beliefs."

Finally, GPTs are characterized by the sequential development of complementary technologies. This sequential development may be seen in the patent record: Citation lags (the time between the patent grant and the arrival of its forward citations) tend to be longer as complementary technologies require more time to develop, citation counts themselves are higher, as GPTs are characterized by a "burst" of invention (Hall & Trajtenberg, 2004). In a GPT, we are also likely to see in the patent record the technologies being adopted in a wide range of industrial sectors, as market actors throughout the economy begin to deploy the technology generally, to many different industrial and technology settings. Therefore, patent records may again be used to offer a window into the development ex post of technologies that build upon, and are complementary to, the focal technology.

6 Conclusion

This study has considered the notion that nanotechnology may be a breakthrough innovation with long-run economic and societal affects—whether it is a "General Purpose Technology" (GPT), and has explored appropriate methodologies to address this question. GPTs are a phenomenon of much interest because these technologies have a profound impact on growth and the productivity levels in the economy and of individual firms, despite initial periods of slowdown as resources are devoted to the development of complementary technologies. Hence, GPTs peak the attention of public and private sector decision makers.

Our literature review demonstrates that there is a growing body of work that considers nanotechnology a GPT. As we show, however, few if any of these studies claiming a nanotechnology-GPT link have developed a systematic approach for determining if this designation is fitting.

The core premise inherent in the characterization of a GPT is that it must meet three criteria: pervasiveness, innovation spawning, and scope for improvement. Our study has highlighted qualitative evidence suggesting that nanotechnology may exhibit characteristics of a GPT. More importantly, we put forth the application of quantitative methods to uncover the nature of nanotechnology. Through the use of patent data, citations analysis, and a "Generality" index derived from patent classifications, we demonstrate that nanotechnology exhibits similar "pervasiveness" levels to that of ICT, an existing GPT. We further propose that patent data may be effectively used to examine "innovation spawning" attributes such as: (1) identifying

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[4] Another problem for any such analysis would arise if the placement of citations by examiners was driven by some internal USPTO job incentive.

a “critical number” (burst) of technologies in intermediate sectors, and (2) the “types” of convergence of believes needed for diffusion to occur. The question is still open regarding how to use quantitative data to solicit information about the scope for future improvements in nanotechnology.

We believe that an effort to evaluate the currently available data through the lens of existing theory and empirical methodology is important for understanding the possible socio-economic implications of nanotechnology during the early phases of dissemination. We conjecture that if nanotechnology is more of an incremental technology, there will be little change in short or long run investment decisions. But if it is a major breakthrough innovation, as a good part of the evidence we explored suggests, disruptions of business routines are to be expected, existing skills may become obsolete more rapidly, and capital shifts from established firms to younger firms of investors that are more likely to embrace the new technology may occur. Moreover we observed the government’s optimal strategy to spur innovation is drastically different when an emerging technology has the character of a GPT than when it is an incremental technology. The level of appropriability of technologies complementary to the core innovation should be lower in the former case than in the latter one. The fast dissemination of complementary technologies associated with an emerging technology is a necessary condition to reach a critical level of acceptability which induces even relatively moderate risk-takers to invest in the emerging technology.

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