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Research Paper

Complexity and the Productivity of Innovation

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Innovation underpins the industrial way of life. It is assumed implicitly both that it will continue to do so, and that it will produce solutions to the problems we face involving climate and resources. These assumptions underlie the thinking of many economists and the political leaders whom they influence. Such a view assumes that innovation in the future will be as productive as it has been in the recent past. To test whether this is likely to be so, we investigate the productivity of innovation in the United States using data from the U.S. Patent and Trademark Office. The results suggest that the conventional optimistic view may be unwarranted. Copyright © 2010 John Wiley & Sons, Ltd.

Keywords complexity; economic theory; history of science; innovation; patents

INTRODUCTION

> Advances in science will . . . bring higher standards of living, will lead to the prevention or cure of diseases, will promote conservation of our limited national resources, and will assure means of defense against aggression (Bush, 1945).

> It is clear that [science] cannot go up another two orders of magnitude as [it has] climbed the last five . . . Scientific doomsday is therefore less than a century away (de Solla Price, 1963).

Industrial societies are the products of invention and innovation, and these remain the twin engines of economic growth (Rosenberg, 1983; Mokyr, 1992; Landes, 1998; Barro and Sala-i-Martin, 2003; Helpman, 2004). This is a recent development. Our ancestors experienced long periods of technological stasis, stretching even to hundreds of thousands of years in the Paleolithic (Ambrose, 2001). Moreover, in human evolutionary history, it may not have been in our best interest to innovate. Research suggests that humans succeed best, not by innovating, but by copying (Rendell *et al.*, 2010). Yet today we have institutionalized innovation, so much so that we now expect frequent technical changes and product cycles lasting only a few months. A

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manufacturer that does not innovate cannot compete, and the same observation applies to nations. So accustomed have we become to innovation that we assume it will continue as a matter of routine. Many people expect innovation to produce solutions to the problems we face in energy, climate and the environment (e.g. Chu, 2009). Our purpose in this paper is to investigate whether we can expect innovation over the long-term to fulfil this role that we have assigned to it.

We contrast here two views of innovation, each leading to different expectations for our future. The first is that innovation is driven mainly by incentives and the supply of knowledge capital, and produces constant or increasing returns (e.g. Baumol, 2002; Scotchmer, 2004). This view underlies much economic thinking, and the policies that derive from it. Provided that markets are undistorted, in this view, innovators will respond to price signals and develop solutions to the problems of the day, whether those problems are shortages of energy or other resources, climate change, or merely a need for a competitive product. A related school of thought suggests that knowledge spillovers facilitate growth through innovation despite diminishing returns to the two traditional economic inputs of capital and labour (Romer, 1986; Lucas, 1988; Aghion and Howitt, 1997). Knowledge spillovers are a form of positive externality through which the results of private efforts at knowledge creation increase the overall stock of ''knowledge capital'' that can be freely accessed by others. Incentives and knowledge capital, then, are the primary constraints to innovation.

The contrary view is that innovation is subject to the evolutionary dynamics of all living systems (Tainter, 1988; Heylighen, 1999; Huebner, 2005). The productivity of innovation is not constant. It varies not only with incentives and knowledge capital, but also with constraints. Research problems over time grow increasingly esoteric and intractable. Innovation therefore grows increasingly complex, and correspondingly more costly. It grows more costly, moreover, not merely in absolute terms, but relatively as well: In the shares of national resources that it requires. Most importantly, as innovation grows complex and costly, it reaches diminishing returns. Higher and higher expenditures produce fewer and fewer innovations per unit of investment. To maintain a constant rate of innovation we must therefore expend ever more resources, and indeed this is what we have been doing (Wolfle, 1960; de Solla Price, 1963; Giarini and Loubergé, 1978; Rescher, 1978, 1980; Rostow, 1980).

We can assess which of these views is more accurate by analyzing patenting activity in the United States, as a proxy measure for innovation. Using data on patents granted by the United States Patent and Trademark Office (USPTO), we examine whether invention exhibits diminishing returns. Our principal conclusion is that, by the data we have and the measure we use, it does. Before presenting our results we describe in more detail the reasoning underlying these disparate views on innovation. Although the literature on these matters distinguishes invention and innovation as different processes, we use the terms interchangeably to indicate the products of systematic attempts to develop technical or conceptual novelties based on understanding of physical, chemical, biological and/or social processes.

INCENTIVES AND INNOVATION

> Scientific and technological discovery and innovation are the major engines of increasing productivity and are indispensable to ensuring economic growth, job creation, and rising incomes for American families in the technologically-driven 21st century (Chu, 2009).

Many of our expectations about the future involve innovation in how we use resources, including energy. Yet resources do not have the same importance in economic theory that they do to physicists or biologists, let alone to those concerned about climate change or other kinds of environmental alteration. Depletion of resources has not been a major concern in conventional economics. The reason is innovation: As a resource

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becomes scarce, it is thought, markets will signal that there are rewards to innovation. Entrepreneurs will discover new resources, or develop more efficient ways of using the old ones, because there are incentives to do so. Consider, for example the following statements:

> No society can escape the general limits of its resources, but no innovative society need accept Malthusian diminishing returns (Barnett and Morse, 1963, p. 139).

> All observers of energy seem to agree that various energy alternatives are virtually inexhaustible (Gordon, 1981, p. 109).

> By allocation of resources to R&D, we may deny the Malthusian hypothesis and prevent the conclusion of the doomsday models (Sato and Suzawa, 1983, p. 81).

There is an assumption to such optimism that is rarely explicated. It is that innovation in the future will be like it has been in the past. That is, we can expect that investments in innovative activities will yield at least the same level of net benefits that they have until today. Innovation in the future will yield constant or perhaps increasing returns. Innovation, in this view, can continue undiminished forever.

If knowledge creation were the exclusive result of individual investments seeking to preclude others from its use, the accumulation of knowledge capital would have ceased long ago. It has been assumed, therefore, that while individual (i.e. firm-level) investments in knowledge capital are subject to diminishing returns, there should be, through knowledge spillovers, increasing returns to knowledge capital in the aggregate. There have been few attempts, though, to address directly the question whether inventive and innovative activities at the *economy-wide level* exhibit diminishing returns. Obviously the advanced economies have continued to generate scientific, technological and organizational novelties, but just as surely, the resources devoted to the pursuit of innovation (in absolute and relative terms) have also grown apace (Clark, 2007).

COMPLEXITY AND INNOVATION

The alternative perspective is that innovation is a complex system embedded within other complex systems. Complexity is here defined in the anthropological sense of increasing differentiation and specialization in structure, combined with increasing integration of parts (Tainter, 1988). Rather than being *sui generis*, innovation is constrained by the same evolutionary factors that regulate all complex systems (Tainter, 1988; Heylighen, 1999). For example, research into the dynamics of complex natural systems with many interconnected and interacting parts has shown that as the intensity of interconnectivity grows, it becomes harder and harder for a system to develop good, never mind optimal, configurations. Stuart Kauffman has dubbed this phenomenon the ''complexity catastrophe'' (Kauffman, 1993).

Complex systems have evolutionary histories, and innovation is no exception. The popular image of science is that of the lone-wolf scholar, an idiosyncratic but persistent genius peering through a microscope or trekking through unexplored jungles (Toumey, 1996). This was indeed how science was conducted through most of the 18th and 19th centuries, the age of naturalists such as Charles Darwin and Gregor Mendel. Yet the naturalists made themselves obsolete as they depleted the stock of general questions that an individual, working alone, could resolve. The principles of gravity, natural selection and inheritance no longer wait to be revealed.

In every field, early research plucks the lowest fruit: The questions that are least costly to resolve and most broadly useful. As general knowledge is established early in the history of a discipline, that which remains axiomatically becomes more specialized. Specialized questions become more costly and difficult to resolve. Research organization moves from isolated scientists who do all aspects of a project, to teams of scientists, technicians and support staff who require specialized equipment, costly institutions, administrators and accountants. The size of inventing teams grows, a phenomenon paralleled in the increasing size of science authorship

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teams (Wuchty *et al*., 2007; Jones *et al*., 2008). Thus, fields of scientific research follow a characteristic developmental pattern, from general to specialized; from wealthy dilettantes and lone-wolf scholars to large teams with staff and supporting institutions; from knowledge that is generalized and widely useful to research that is specialized and narrowly useful; from simple to complex and from low to high societal costs.

As this evolutionary pattern unfolds, the resources and preparation required to innovate increase. In the first few decades of its existence, for example, the United States gave patents primarily to inventors with minimal formal education but much hands-on experience. After the Civil War (1861–1865), however, as technology grew more complex and capital intensive, patents were given more and more frequently to college-educated individuals. For inventors born between 1820 and 1839, only 8 per cent of patents were filed by persons with formal technical qualifications. For the 1860–1885 birth cohort, 37 per cent of inventors were technically qualified and ''. . . they produced 45.1 per cent of patents, 52.1 per cent of assignments, 40.4 per cent of all long-term citations, and 60.9 per cent of inventor citations'' (Khan, 2005, pp. 211–212).

It has long been known that within individual technical sectors, the productivity of innovation reaches diminishing returns. Hart (1945) showed that innovation in specific technologies follows a logistic curve: Patenting rises slowly at first, then more rapidly and finally declines. Rostow (1980, p. 171) extended this observation in his attempt to explain why economic growth slows in developed countries. The question before us is: Does the phenomenon of diminishing returns to innovation in individual sectors apply to innovation as a whole? Max Planck thought so. Rescher (1980, p. 80), paraphrasing Planck, observed that ''. . . with every advance [in science] the difficulty of the task is increased''. Writing specifically in reference to natural science, Rescher suggested:

> Once all of the findings at a given state-of-the-art level of investigative technology have been realized, one must move to a more expensive level . . . In natural science we are involved in a technological arms race: with every ''victory over nature'' the difficulty of achieving the breakthroughs which lie ahead is increased (1980, p. 94, 97).

Rescher terms this ''Planck's Principle of Increasing Effort'' (1978, pp. 79–94). Planck and Rescher suggest that *exponential* growth in the size and costliness of science is needed just to maintain a *constant* rate of innovation. Science must therefore consume an ever-larger share of national resources in both money and personnel. Schmookler (1966, pp. 28–29), for example showed that while the number of industrial research personnel increased 5.6 times from 1930 to 1954, the number of corporate patents over roughly the same period increased by only 23 per cent. Such figures prompted Wolfle (1960) to pen an editorial for *Science* titled ''How Much Research For a Dollar?'' de Solla Price (1963) observed in the early 1960s that science even then was growing faster than both the population and the economy and that, of all scientists who had ever lived, 80–90 per cent were still alive at the time of his writing.

The stories that we tell about our future assume that innovation will allow us to continue our way of life in the face of climate change, resource depletion and other major problems. The possibility that innovation overall may produce diminishing returns on knowledge capital calls this future into question. As de Solla Price (1963, p. 19) pointed out, continually increasing the allocation of personnel to research and development cannot continue forever or the day will come when we must all be scientists. It is therefore important to determine whether the research enterprise overall produces diminishing returns.

THE PRODUCTIVITY OF CONTEMPORARY INNOVATION

The discussion to this point suggests two alternative hypotheses for the development of innovation in the aggregate: (a) That while innovation may reach diminishing returns in individual fields, knowledge spillovers and

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perhaps other factors produce constant or increasing returns overall; or (b) that increasing difficulty and complexity in research produce diminishing returns to innovation overall.

One type of intellectual activity with important consequences for technological and economic development is invention—the creation of new devices, methods and processes—and one type of invention, that which results in the granting of a patent, has become a widely used metric in studies of the ''knowledge economy'' (e.g. Acs and Audretsch, 1989; Griliches, 1990; Jaffe *et al*., 1993; Jaffe and Trajtenberg, 2002; Bettencourt *et al*., 2007). We can therefore use the economy's production of patented inventions to examine whether the productivity of invention has been increasing or decreasing.

While patent statistics are not a perfect measure of creative productivity in science and engineering (e.g. McGregor, 2007), they are still remarkably robust as an indicator of overall innovative activity both within and without the commercial arena. In the United States, commercial invention and innovation have been driven largely by the private sector, and the individuals and firms involved have been keen to obtain legal protection for their intellectual property (Lamoreaux and Sokoloff, 1999; Hughes, 2004). In the academic sector the primary motivations have been advancement and recognition, obtained through publishing. Nevertheless, both private sector and academic innovation show similar trends. Figure 1 shows the correlation between science and engineering papers published by U.S. authors and patent applications submitted by U.S. residents. The correlation between the two data sets ($r = 0.81$) accounts for 66 per cent of their variance. Moreover, about 50 per cent of U.S. patents are granted to foreign entities. For these reasons we consider U.S. patent data reliably to indicate the productivity of innovation in the United States and globally.

There are at least four ways to measure the productivity of inventive activity, and each one informs us of something different:

Patents/Population (patents per capita)
Patents/GDP
Patents/R&D Investments
Patents/Inventor

We focus here primarily on patents per inventor. This productivity measure is the counterpart to the most widely used measure

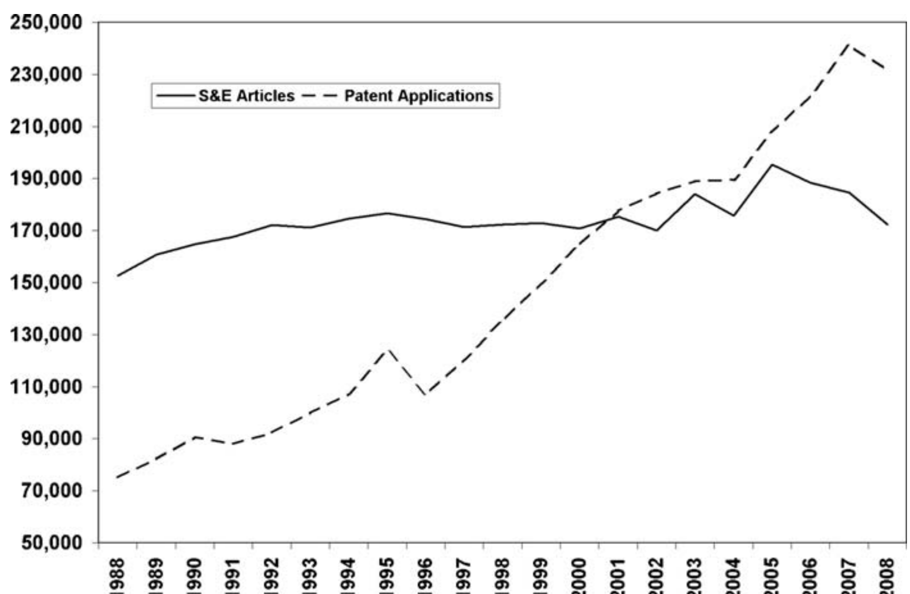

Figure 1 Trends in science and engineering articles published by U.S. authors (excluding psychology and social sciences) and patent applications by U.S. inventors, 1988–2008. Data from National Science Board (2008, 2010)

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for the productivity of an economy or industry, namely output per unit of labour measured in physical or monetary units.

Using data provided by the United States Patent and Trademark Office (USPTO) we have constructed a database on patenting in the United States. The construction of the database is described in detail in Lobo and Strumsky (2008) and Marx *et al.* (2009). The database covers the period 1970–2005 and includes information on almost 5 million utility patents and over 1.5 million uniquely identified inventors. (A utility patent—also referred to as ''patents for invention''—is issued for the invention of ''new and useful'' processes, machines, artefacts or compositions of matter. More than 90 per cent of the patents granted by the USPTO are utility patents.) A patent is counted in the year it was successfully applied for so as to count inventions close to the time they were invented. When the USPTO grants a patent it classifies the patent's technology through a numerical system of technology classes and subclasses. The patent's primary technology identifier is its primary class number, of which currently there are 481. (Two examples are class 205, electrolysis processes and class 850, scanning probe microscopy.) We have used technology classes to identify the technology represented by a patent, and have grouped technology classes into technology sectors or industries. A listing and description of patent technology classes can be found at www.uspto.gov/web/patents/classification/selectbynum.htm. Table 1 shows the USPTO categories that comprise the industries in Figures 3–7. The USPTO's electronic data files are incomplete for years before 1973. To have the most reliable patent counts possible we begin the analysis in 1974, except for the new sectors of biotechnology and nanotechnology, which were established in 1980. Since it takes 3–5 years, on average, for a patent to be approved, we end the analysis in 2005.

Figure 2 shows that over the period 1974–2005, the average size of a patenting team increased by 48 per cent. This parallels the trend toward increasing numbers of authors per scientific

Table 1 Technology classes employed in Figures 3–7

Technology sector	USPTO technology classes
Surgery & Medical Instruments	128, 600, 601, 602, 604, 606, 607, D24
Metalworking	29, 72, 75, 76, 140, 147, 148, 163, 164, 228, 266, 270, 413, 419, 420, 59, 245
Optics	352, 353, 355, 359, 396, 398, 399, D16
Drugs	424, 514
Chemicals—Crystal	117, 349
Chemical—General Compounds and Compositions	156, 196, 208, 260, 423, 501, 502, 516, 532, 585, 930
Chemical–Physical Processes	23, 216, 222, 252, 261, 366, 416, 494, 503
Gas Power	48, 55, 95, 96
Power Systems	60, 136, 290, 310, 318, 320, 322, 323, 361, 363, 388, 429
Solar energy	126, 136, 165, 257, 320, 322, 323, 326, 438, 505
Wind energy	290, 415, 416, 417
Communications	178, 333, 340, 342, 343, 358, 367, 370, 375, 379, 385, 455
Computer Hardware	345, 347, 360, 365, 369, 708, 709, 710, 711, 712, 713, 714, 720
Computer Software	341, 380, 700, 701, 702, 703, 704, 705, 706, 707, 715, 716, 717, 718, 719, 720, 725, 726
Biotechnology	435, 800
Nanotechnology	977

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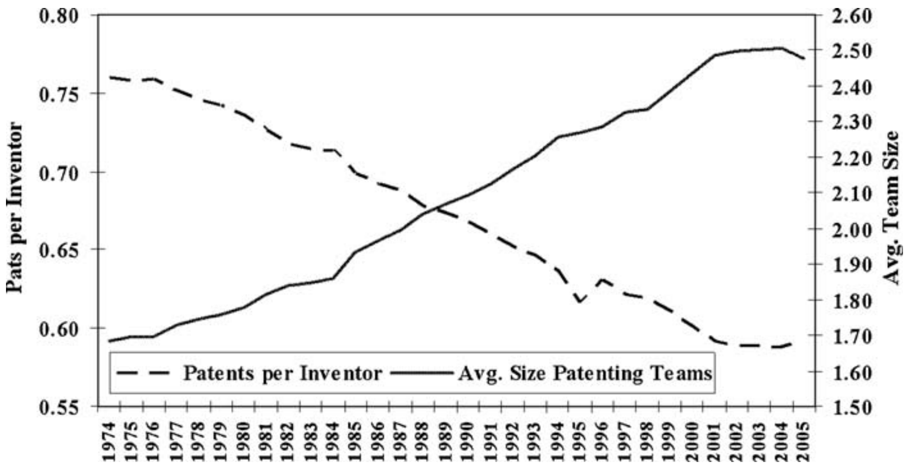

Figure 2 Average size of patenting teams and patents per inventor, 1974–2005

paper (Wuchty *et al.*, 2007; Jones *et al.*, 2008). de Solla Price (1963, pp. 102–103) observed this phenomenon early on, and noted that increasing the gross number of scientists has the primary consequence of increasing the pool of scientists who are of average ability. He therefore attributed the phenomenon of increasing team size to ''. . . the constant shift of the Pareto distribution of scientific productivities'' (de Solla Price 1963, p. 89). That is, as the most prolific authors become more productive, and those less productive become more numerous, it is natural that those who are more productive form teams of those who are less so. We suggest that while the mechanism Price postulates may be at work to some degree, it is more likely that increasing numbers of authors in both invention and publication derive from the same source. This is the increasing complexity of the research enterprise, necessitated by increasing difficulty in the questions addressed or the breakthroughs sought and leading to the incorporation of more and more specialties in an individual project (Rescher, 1978, 1980).

The enterprise, moreover, seems to be producing diminishing output per inventor. Over the

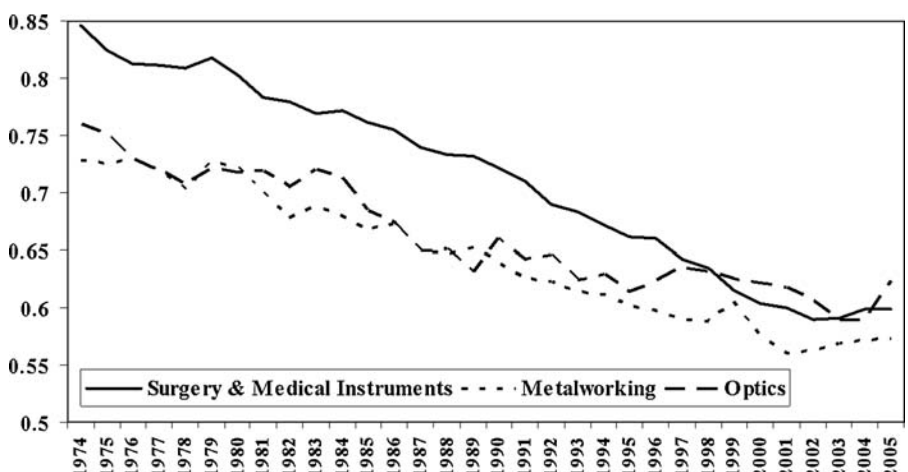

Figure 3 Patents per inventor in surgery and medical instruments, metalworking and optics, 1974–2005

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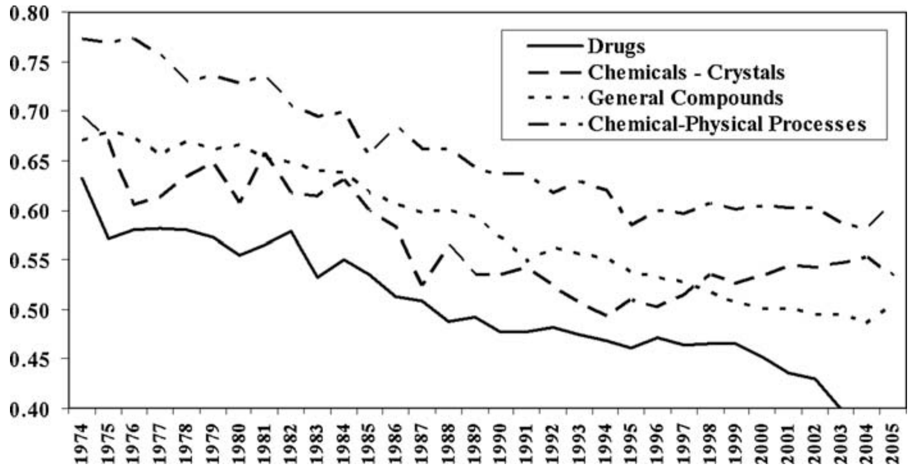

Figure 4 Patents per inventor in drugs and chemicals, 1974–2005

period shown in Figure 2, as the size of patenting teams inexorably grew, patents per inventor declined by 22 per cent. This is averaged over all technical fields, and shows the productivity of the inventive workforce as a whole. Yet new fields of innovation are usually more productive than old ones, since in new fields simpler, basic discoveries can still routinely be made. It is appropriate therefore to ask whether there are increasing returns to innovation in newer technical fields and, if so, whether these offset diminishing returns in older fields.

Figures 3 and 4 show patents per inventor in several technical sectors that are long-established, and in which there are still active research programs. While each field shows short-term fluctuations, the trend in each of them is a decline in patents per inventor. Since these are older fields, this finding would be expected.

Figure 5 combines several energy technologies, both ones that are older and ones that are newer. Each sector shows declining patents per inventor. The most disturbing aspect of this chart is that solar and wind power technologies show the same trend as older gas and power system sectors. It is widely believed that solar and wind energy will be needed to power industrial societies in the future. Yet it appears that our

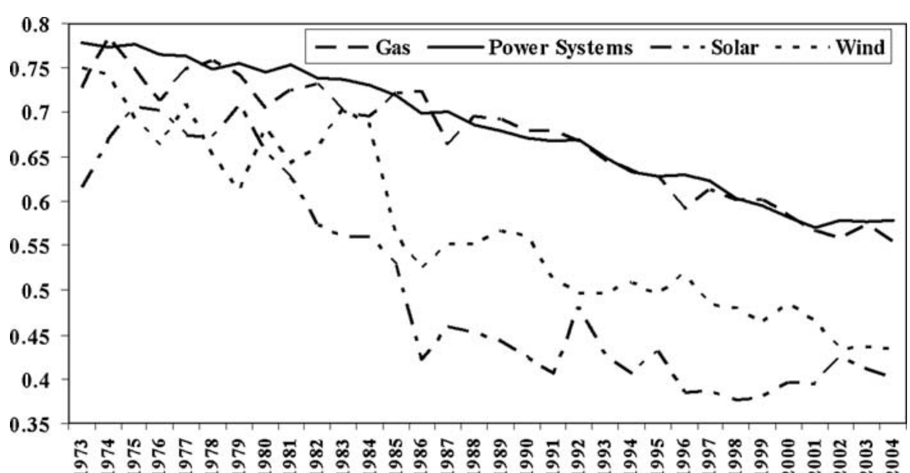

Figure 5 Patents per inventor in energy technologies, 1974–2005

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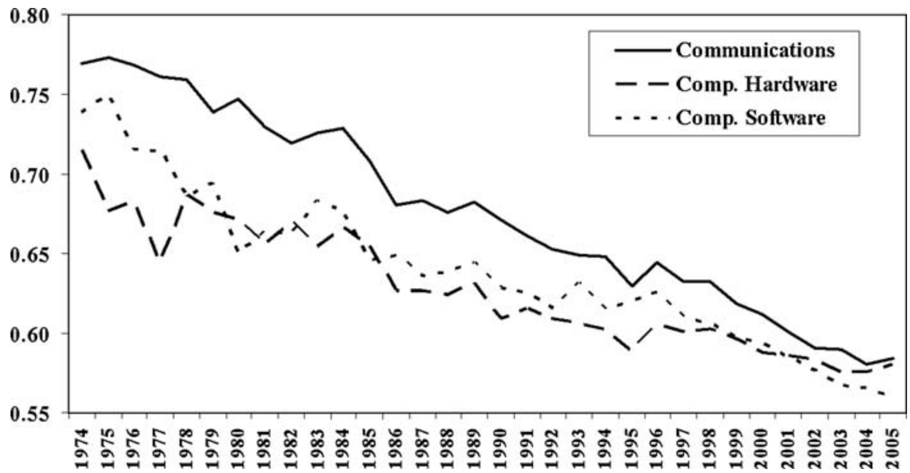

Figure 6 Patents per inventor in information technologies, 1974–2005

investments in improving technologies in these sectors are producing diminishing returns, and that these sectors may be approaching technical maturity.

The precipitous drop in renewable energy patents in the early 1980s may be attributable to the end of the U.S. federal tax credits for renewable energy installations. The decline in oil prices in the late 1980s further reduced incentives to innovate in this sector. Yet the continued decline since 1990 confirms our assessment that, notwithstanding exogenous factors, there is diminishing productivity of innovation in renewable energy technologies.

Figure 6 tracks patents per inventor in the relatively newer fields of information technology, both hardware and software. These are some of our most dynamic technical sectors, and the sources of much recent economic growth. Yet each of these technical sectors shows a long-term trend of declining productivity per inventor.

Even some of the newest technical fields, biotechnology and nanotechnology, show this trend (Figure 7). Inventive efforts in these sectors are producing declining rates of innovation. If this is characteristic of newer fields more broadly, then in industrial economies there may no longer be increasing returns in newer sectors to offset diminishing returns in older ones.

One can also attempt to measure the productivity of innovation by returns on financial capital and direct investment. This is shown in

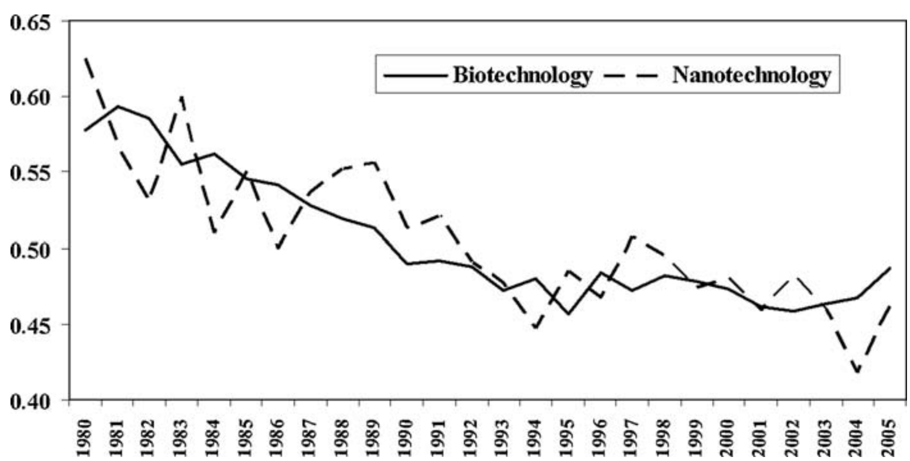

Figure 7 Patents per inventor in biotechnology and nanotechnology, 1980–2005

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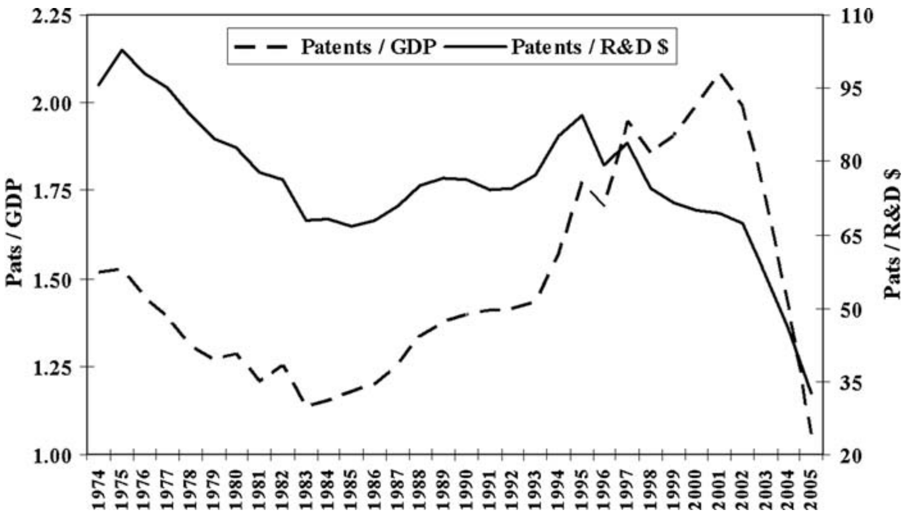

Figure 8 Patents per $100 000 000 of gross domestic product (GDP) and patents per $100 000 000 of research and development (R&D) expenditures, 1974–2005

Figure 8 as patents per $100 000 000 of gross domestic product (GDP) and patents per $100 000 000 of research and development expenditure. The results require care in interpretation, for the beginning and end of the chart are not comparable. Beginning in 1982, Congress changed how the U.S. patent system operated by establishing a system of specialized patent appeals. In the 1990s, Congress followed with changes in how the USPTO was financed, by essentially creating a fee-for-service operation. The new legal and organizational regime for the USPTO made it easier to get a patent and to pursue infringement cases, while settlements for infringement became substantially larger. These factors combined to alter significantly the value of owning a patent, and led to a sharp and continuing increase in patenting activity (Jaffe and Lerner, 2004). Figure 8 shows this increase. Prior to these developments the trend of innovative productivity was downward in respect to financial capital and direct investment. The results shown in Figure 8 are not, therefore, inconsistent with the results seen in Figures 3–7.

Finally, in an attempt to measure complexification, Figure 9 shows the average number of

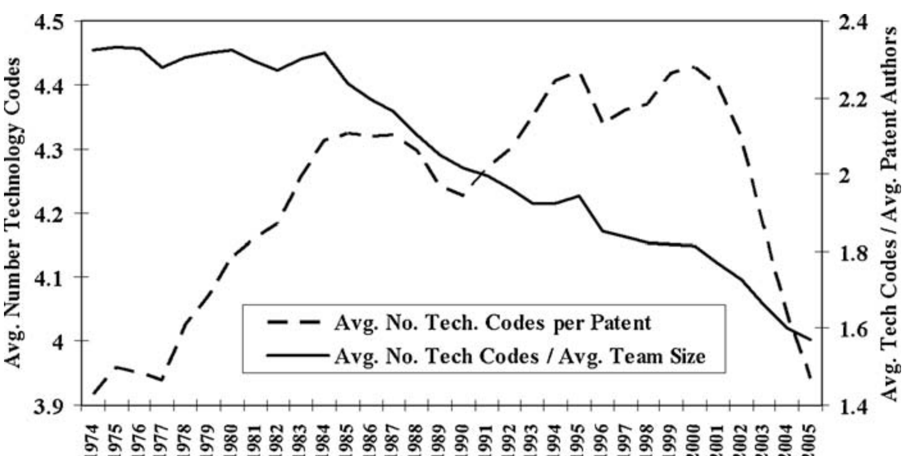

Figure 9 Average number of technology codes per patent, and ratio of technology codes to authors per patent, 1974–2005

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technology codes per patent and the ratio of technology codes to authors per patent. Technology codes are used by the USPTO to classify a patent's technology. The results show an increasing number of technology codes per patent through 1995, a slight contraction and approximately a plateau through 2000, followed by a decrease through 2005. The results need clarification. Patents with more technology codes need more than the average 3–5 years to process, and are harder to get awarded. Thus, the decline in the last few years of this chart is an artefact of the increased evaluation time needed for more complex patents. With this caveat in mind, the chart shows a trend of increasing complexity per patent through 2000, with incomplete results thereafter. At the same time, technology codes per patenting author declined throughout this period.

We suggest some interpretations based on this graph, acknowledging that these require further investigation. It seems that firms are increasing the size of innovation teams (Figure 2) faster than they are increasing the technical diversity of such teams (Figure 9). This suggests that firms are adding more of the same kind of specialist in preference to more kinds of specialists. It may be that firms or the members of research teams do not recognize the need for more specialties, or that firms are resisting further complexification. Given that complexity costs, the latter would be understandable. It is also likely that technology codes per patent are holding roughly steady or increasing but that, along with the rest of science, innovations are becoming more technically narrow. Part of firms' strategy to avoid increased processing time for more complex patents is to break these innovations down into narrower claims.

A number of questions arise here: Are there limits to the number of technical sectors that a firm can manage in a project? Are there upper limits to how much complexity can be managed in the innovative process? Is the cost of complexity inhibiting its further emergence? Do firms lack administrative or information systems capable of integrating sufficient complexity? These are rich topics for further study.

SUMMARY AND CONCLUSIONS

> Now, *here*, you see, it takes all the running *you* can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that! (Carroll, 1872)

Scientific fields undergo a common evolutionary pattern. Early work establishes the boundaries of the discipline, sets out broad lines of research, establishes basic theories and solves questions that are inexpensive but broadly applicable. Yet this early research carries the seeds of its own demise. As pioneering research depletes the stock of questions that are inexpensive to solve and broadly applicable, research must move to questions that are increasingly narrow and intractable. Research grows increasingly complex and costly as the enterprise expands from individuals to teams, as more specialties are needed, as more expensive laboratories and equipment are required, and as administrative overhead grows (Rescher, 1978, 1980). This much has been suspected since at least 1879 (Peirce, 1879), and there are indications that the productivity of innovation reached a peak in the 1870s (Huebner, 2005). Notwithstanding this phenomenon, it has been argued that knowledge spillovers across sectors produce positive returns overall to innovation (Romer, 1986; Lucas, 1988; Aghion and Howitt, 1997). Yet in the data examined here, the latter outcome is clearly not the case. Measured as patents per inventor, our investments in technical research and development appear to be yielding declining outputs.

We have an impression today that knowledge production continues undiminished. Each year sets new records in numbers of scientific papers published. Breakthroughs continue to be made and new products introduced. Yet we have this impression of continued progress not because science is as productive as ever, but because the size of the enterprise has grown so large. Research continues to succeed because we allocate more and more resources to it. In fact, the enterprise does not enjoy the same productivity as before. It is clear that to maintain

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the same output per inventor as we enjoyed in, say, the 1960s, we would need to allocate to research even greater shares of our resources than we now do. Without such an allocation, the productivity of research declines.

A consideration in our analysis is that we can measure only quantities of innovation, not quality nor increments of improved functionality. Yet the characteristic evolution of a technology is logistic: Innovations come slowly at first, then accelerate, and finally come more slowly and with greater difficulty (Hart, 1945). Throughout this sequence, early innovations will ordinarily give the largest increments of improvement, while with later innovations the increments of improvement become progressively smaller and harder to achieve (Wilkinson, 1973, pp. 144–145). We expect, therefore, that declining patenting per inventor truly reflects diminishing productivity that is not offset by greater increments of improvement per innovation.

Based on these results, we reject the hypothesis that knowledge spillovers or other factors produce constant or increasing returns generally in innovative activities. We are swayed instead by the alternative hypothesis, that increasing complexity in research is causing the enterprise overall to produce diminishing returns.

This finding has implications of great importance for the future of industrialized nations, and indeed of all nations. We have become accustomed to high levels of employment and continual growth in material well-being, both arising from the scientific enterprise. So accustomed are we to scientific achievement that we have based our continued well-being on the assumption that knowledge production will continue in the future as we have known it in the recent past. That is, we assume that science will continue to provide both the innovations needed for continued prosperity and those needed to combat problems of climate change and resource depletion (e.g. Chu, 2009). These expectations might be realistic if research could produce increasing or even constant returns. It appears, however, that it cannot. Our investments in science have been producing diminishing returns for some time (Machlup, 1962, p. 172, 173). To sustain the scientific enterprise we have employed increasing shares of wealth and trained personnel (de Solla Price, 1963; Rescher, 1978, 1980). There has been discussion for several years of doubling the budget of the U.S. National Science foundation. Allocating increasing shares of resources to science means that we can allocate comparatively smaller shares to other sectors, such as infrastructure, health care, or consumption. This is a trend that clearly cannot continue forever, and perhaps not even for many more decades. Derek de Solla Price suggested that growth in science could continue for less than another century. As of this writing, that prediction was made 47 years ago (de Solla Price, 1963). Within a few decades, our results suggest, we will have to find new ways to generate material prosperity and solve societal problems.

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