TECHNOLOGICAL REGIMES: THEORY AND EVIDENCE

Orietta Marsili

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ECIS, Eindhoven University of Technology, P.O. Box 513,
5600 MB, Eindhoven, The Netherlands, and
SPRU, Mantell Building, University of Sussex,
Brighton, BN1 9RF, UK
E-mail: o.marsili@tm.tue.nl,

Abstract

This paper deals with the diversity of patterns of innovation across industrial sectors and the definition of technological regimes. Technological regimes are important because they identify common properties of innovative processes in distinct sets of production activities. Such properties contribute to interpreting asymmetries in the dynamics of industrial competition. This paper revises the prevailing definition of technological regimes and provides a systematic summary of the evidence by developing a new typology of regimes. The analysis suggests that the concept of technological entry barriers might be a more useful concept than that of appropriability. The distinction between technologies and products is also revealed important to assess features of regimes that are independent on the characteristics of particular technologies, such as the complexity of knowledge bases and the diversity of search trajectories. Last, the importance of inter-firm diversity in innovative environments is revised; in areas of high technological opportunities, technological regimes impose stronger imperative on the rates and directions of firms' search.

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Section one: Introduction

This paper is concerned with inter-industry differences in the properties of innovative processes and in the nature of the knowledge bases that underlie such processes. The purpose of the paper is twofold. It provides a systematic summary of the empirical evidence on the sectoral diversity in the process of technical change. It revises the prevailing definition of technological regimes (Nelson and Winter 1982). It argues that the concept of technological entry barriers may provide to be more useful concept than that of appropriability in the interpreting the diversity of industrial dynamics.

Formal evolutionary models of industrial competition (Nelson and Winter 1982, Dosi et al. 1995) have shown that sectoral asymmetries in industrial dynamics can be interpreted on the grounds of technological regimes. Regimes are defined by the combination of factors including the level of technological opportunity for established firms, the ease of access to new technological opportunity by entrant firms, and the cumulativeness of learning. This paper argues that when a further distinction between technologies and products is made, it is possible to account for additional fundamental dimensions of technological regimes. The distinction between technologies and products allows for the representation of the complexity of the knowledge base and the diversity of technological trajectories within an industry. These dimensions are independent on the conditions of technological opportunity associated with the single fields of knowledge relevant for innovation. The complexity of the knowledge base and the homogeneity of technological trajectories represent possible sources of technological entry barriers in the industry and therefore contribute to shape the dynamics of industrial competition.

The paper extends previous taxonomic exercises of technological regimes undertaken by Pavitt (1984) and Malerba and Orsenigo (1996). As in these studies, the paper relies on two basic assumptions. Firstly, it is assumed that, although institutional factors may influence the process of technical change at country level (Lundvall 1992), the properties of innovation processes are, to a significant extent, invariant across countries and specific to technologies or industrial sectors (Malerba and Orsenigo 1996). Secondly, following previous approaches (Nelson and Winter 1982) it is assumed that general properties in innovation processes, which are shared by a population of firms independently of the variety of idiosyncratic behaviours observed at the firm level can be identified.

In this paper, a typology of technological regimes is identified. This typology is based on the industry-specific properties of innovative processes, sources of knowledge and nature of knowledge bases. In this sense, it differs from classifications based on the nature of production processes (Woodward 1980), or the nature of products (Hobday 1998). The regimes are distinguished through an analysis of the technological activities of firms in different industries. The empirical data is drawn from primary sources, such as US patent data, SPRU database on the world's largest firms, national statistics on R&D expenditure and personnel, and secondary sources, such as qualitative surveys of R&D executives, and bibliometric data on scientific input. The discussion on technological regimes also draws on the literature on the microeconomic dynamics of technical change.

The paper is divided into five sections. Section two explores the characteristics of technological regimes also in relation to previous taxonomic exercises of sectoral patterns of innovation. Section three suggests a new typology of technological regimes, drawn from empirical evidence and section four explores the implications of the new typology of regimes for understanding innovation. Section five is the conclusion.

Section Two: The characteristics of technological regimes

This section reviews the characteristics of technology regimes. It brings together the literature on technological regimes and discusses the various elements that different authors have identified in their studies of technical change. These elements are analysed empirically in section three.

A 'technological regime' (Nelson and Winter 1982, Winter 1984) or 'technological paradigm' (Dosi 1982) defines the nature of technology according to a knowledge-based theory of production (Rosenberg 1976). Innovation is viewed as a problem-solving activity drawing upon knowledge bases that are stored in routines (Nelson and Winter 1982). Accordingly, the technology is represented as a technological paradigm defining "a pattern of solution to selected technological problems based on selected principles derived from natural sciences and selected material technologies" (Dosi 1982:). In a similar way, a technological regime defines the particular knowledge environment where firm problem-solving activities take place (Winter 1984).

Technological regimes are important because they constraint the pattern of innovation emerging in an industry. In the literature, two opposite types of regimes are identified.

Such identification of regimes is based on the role that new and established firms play as sources of innovation within an industry. An *entrepreneurial regime* facilitates the entry of new innovative firms, while a *routinised regime* facilitates innovation by incumbent firms (Winter 1984). This distinction originates from Schumpeter's conceptions of innovation, associated with different historical phases of economic development (Schumpeter 1934, 1942). These regimes are referred to as *Schumpeter Mark I*, and *Schumpeter Mark II* (Freeman 1982: recently developed by Malerba and Orsenigo 1996).

Taxonomic exercises of firm innovative activities have identified divergent patters of innovation that prevail in distinct sets of production activities. These taxonomies often overlap with industrial classifications, but often taxonomies group production activities that do not belong to the same sector. Pavitt (1984) distinguished the structural and organisational traits of innovative firms in *science-based* (electrical/electronics and chemicals), *specialised suppliers* (non-electrical machinery, instruments, and speciality chemicals), *supplier dominated* (paper and textiles), and *scale intensive* (food, vehicles and metals). Malerba and Orsenigo (1996) classified technologies into two general patterns of innovation. The *Schumpeter Mark I* pattern of innovation is characterised by a dispersed and turbulent structure of innovative activities, prevailing in non-electrical machinery, instruments and traditional technologies. The *Schumpeter Mark II* pattern of innovation is distinguished by a concentrated and stable structure of innovative activities, typical of chemical and electrical-electronic technologies. These diverse patterns of innovation across sectors or technologies can be attributed to differences in the nature of technological regimes. Dosi lists three characteristics, which help to define a regime: (i) the properties of the learning processes associated with the solution of technological problems in firm's innovation and production activities; (ii) the system of sources of knowledge, internal and external to the firm, relevant for such problem solving activities; (iii) the nature of the knowledge base upon which firms draw in solving technological problems (Dosi 1982).

2.1. Learning

The properties of technological learning play an important role in defining a technological regime. Malerba and Orsenigo identify three different properties of learning: technological opportunity conditions, appropriability conditions, and cumulativeness of learning (Dosi and Orsenigo 1988, Malerba and Orsenigo 1990, 1993). Technological opportunity conditions characterise the range of possible technical solutions to firms problem-solving activities and the ease with which such solutions can be achieved. The appropriability conditions express the ease of protecting the results of innovation against imitation from competitors, and the means of appropriation used by firms. The degree of cumulativeness of innovation defines to what extent technical solutions are incrementally built upon those already achieved by a firm. Cumulativeness in innovation may arise from different sources: the intrinsic cumulative and self-reinforcing nature of cognitive processes (Rosenberg 1976); the local nature of search (Pavitt 1984); the organisation of firm search in R&D laboratories; the internal funding of more R&D activities through profits from earlier innovative successes (Malerba and Orsenigo 1993).

The characterisation of sectoral patterns of innovation made by Malerba and Orsenigo (1996) is consistent with the definition of technological regimes in terms of opportunity, appropriability and cumulativeness of innovation. Malerba and Orsenigo (1990, 1997) argue that conditions of high technological opportunity, low appropriability and low cumulativeness lead to a Schumpeter Mark I pattern of innovation in mechanical industries. Conversely, conditions of high technological opportunity, high appropriability and high cumulativeness underlie the emergence of a Schumpeter Mark II pattern of innovation in chemical and electrical-electronic industries. Therefore, different patterns of innovation in areas of high technological opportunities are explained on the grounds of differences in appropriability and cumulativeness conditions.

2.2. Technological entry barriers

The analysis of regimes in this paper partly departs from Malerba and Orsenigo. It focuses on the concept of technological entry barriers rather than on the concept of appropriability. In this respect, the analysis builds upon Pavitt's taxonomy in which innovative activities across sectors are characterised by distinct combinations of level of technological opportunity, threat of technology-based entry, and appropriability (Pavitt, Robson and Townsend 1989). Technological entry barriers in an industry are defined by the ease with which external firms access a certain pool of technological opportunities, that is, the ease of innovative entry in the industry. They define the competitive advantage that any established firm can gain as outcome of innovation with respect to its potential competitors from outside the industry. Conversely, the appropriability of innovation defines the competitive advantage that an innovator can acquire with respect to all its potential competitors from inside and outside the industry. The notion of technological entry barriers captures the dynamics of industrial competition driven by the entry of firms in an industry more accurately than the concept of appropriability.

In addition, the distincion between appropriability and technological entry barriers is important because it allows representing regimes in which different conditions of appropriability and technological entry barriers may coexist. Patters of innovation characterised by high concentration of innovative activities in few leading firms, combined with volatility in the relative position of major innovators, as observed for example in the aircraft-engine industry (Bonaccorsi and Giuri 1999), could be interpreted as an outcome of the combination of high technological entry barriers and low appropriability conditions.

Different sources of entry barriers can be identified in relation to the properties of learning processes and the nature of the knowledge base. One source arises from the specificity knowledge to industrial applications (Winter 1987). As illustrated by Rosenberg (1976), the process of technological convergence in the application of mechanical competencies in a wide set of production activities lead to a process of vertical disintegration of production activities. New specialised firms entered the machine tools industry as spin-offs of established firms active in other industries. Another source of technological entry barriers is represented by the existence of advantages related to the scale of production in innovative processes (Chandler 1990). Various factors are suggested as leading to the advantage of large firms in innovation, such as static scale economies in R&D activities, dynamic scale economies along learning curves, ease of access to internal funding for risky research projects with imperfect capital markets, etc. (Scherer and Ross 1990).

The cumulative nature of learning may also generate innovative advantages for large firms. As result of cumulative innovative processes, established firms may expand their scale of production persistently over time, and become more innovative (Dosi et al. 1995). In this case, a positive relationship between firm size and innovation would emerge as the outcome of cumulative learning rather then revealing the existence of scale economies in innovation. Lastly, technological entry barriers can arise from the requirements of in-house technical competencies and complementary assets in innovation processes (Teece 1986). These various sources of technological entry barriers can have a different impact of innovative entry. For example, the industry-specificity of knowledge bases may represent a major obstacle for innovative entry by diversification of established firms, while scale and in-house advantages in innovation may prevent more effectively the entry of new innovative firms.

2.3. *Technological diversity*

The degree of intrasectoral diversity in firm innovative processes is often regarded as another factor defining in a technological regime (Dosi and Orsenigo 1988, Malerba and Orsenigo 1990). Technological diversity reflects the number of possible 'technological trajectories' along which the normal process of technological learning take place, and the idiosyncratic ability of any firm to exploit a selected trajectory, ability that depends on specific capabilities, tacit knowledge and strategic behaviour (Rosenberg 1976, Nelson and Winter 1982, Dosi 1988). A technological regime constrains the set of trajectories that a firm may explore (Dosi 1982), as well as the range of available strategies, competencies and forms of organisation of innovation processes in a firm (Malerba and Orsenigo 1993). The degree of technological diversity among firms within any industry inversely defines the 'strength' of a technological regime upon the discretionary behaviour of individual firms. As stressed by Malerba and Orsenigo (1990)

> [I]n some cases the knowledge base is such that firms are compelled to explore the same set of cognitive and technological fields and to adopt the same search procedures. In other cases, the knowledge base instead allows firms to pursue different behaviours (Malerba and Orsenigo, p. 291)

2.4. *Technological diversification*

Other studies have focused on the character of the diversification of technological competencies by firms in an industry (Robson, Townsend and Pavitt 1988, Patel and Pavitt 1994, Granstrand, Patel and Pavitt 1997). These studies argue that the extent to which firms undertake processes of technological diversification depends on two factors: i) the possibility for a firm to exploit emerging technological opportunities, and ii) the need to co-ordinate different technologies due to the complexity of the final products and/or production processes (Granstrand, Patel and Pavitt 1997). In the first case, Patel and Pavitt (1997) suggests that at the early stages of development of a new technology, under conditions of high uncertainty, firms may accumulate marginal competencies in the new field. However, as firms identify and explore the rich set of potential technical solutions, they may accumulate background or even core competencies in the emerging field. Due to the initial distance of firm's competencies from emerging technologies, high opportunities for innovation may lead to an increasing level of differentiation of the knowledge base. In the second case, observe Patel and Pavitt (1997), in order to introduce new or improved solutions to their complex products and production processes firms need to identify, integrate and adapt to their specific requirements new or improved materials, components and production machinery from their suppliers. Background competencies in instrumentation and production technologies often become essential for a firm to fully benefit from innovations along a complex supply chain.

2.5. Sources of knowledge

The innovative success of a firm depends on its ability to effectively co-ordinating and integrating a range of internal and external sources of scientific and technological knowledge (Freeman 1982). These external sources of knowledge reside in competing firms; in firms active in downstream and upstream industries along the vertical chain of production (i.e. users and suppliers); and in institutions outside the industrial system (e.g. universities etc.). Inside a firm, new knowledge is acquired through formal search in R&D laboratories, and through more informal learning in all range of firm activities (i.e. production, design, marketing, etc.). The sources of knowledge most important for innovation are specific to a technological regime. They contribute to define both the general level of technological opportunity and the ease and main potential channels of technology-based entry in an industry (Winter 1984). As stressed by Winter (1984) "the potential entry is likely to be roughly proportional to the number of people exposed to the knowledge base from which innovative ideas might derive". Although a large exposure to the same knowledge base favours potential entry, the actual decision of entry is likely to occur if the knowledge base does not have a complex and systemic nature, Winter argues. A complex knowledge base implies that a firm needs to manage and integrate a variety of technological competencies, some of which are internally developed, and some are external to the firm (Malerba and Orsenigo 1993).

The distinction made between appropriability and technological entry barriers is important in terms of understanding the relationship between the relevance of the various sources of knowledge and the other characteristics of technological regimes. For example, the contribution of users may reduce the strength of technological entry barriers in an industry, while the contribution of suppliers may decrease the appropriability of innovation[1]. This is because users share 'productive knowledge' with the firms in an industry and can therefore develop technological competencies that enable them to develop a new product and enter the industry. In contrast, in industries where innovation relies on the knowledge contribution of suppliers, which is generally

[1] Pavitt personal conversation

embodied in capital goods and intermediate products, appropriability is low as competing firms may easily access to the same sources of equipment.

Scientific advances originating outside the industrial system, mainly from academic research, represent an important source of knowledge for the innovative processes of firms (Mansfield 1991, Klevorick et al. 1995, Martin et al. 1996, Pavitt 1998). Scientific advances increase the general level of technological opportunity. At the same time, they influence the mechanisms of exploitation of new technological opportunities by established firms as compared to new firms. The extent to which scientific advances may strengthen technological entry barriers or rather vehicle the innovative entry of new firms in an industry depends on the degree to which such advances can be easily translated into more applied research industrial (Winter 1984).

The closeness of a technology to science is important also in relation to another property of a technological regime that can be described as '*technological richness*'. Such a property reflects the fact that in some circumstances, technologies enable certain specific industries to generate a continuous stream of new products. Because of the 'universal' nature of scientific knowledge, scientific advances create new opportunities for innovation across a variety of products in an industry. That is, the closeness of science of a technological regime increases the 'technological richness' of opportunities for innovation. Under these circumstances, the level of technological opportunity can increase for both established firms and potential entrants, leading eventually to simultaneous conditions of high levels of technological opportunity and low technological entry barriers.

2.6. The nature of knowledge

The nature of knowledge differs across regimes in terms of tacitness, observability, complexity, and systemic nature (Winter 1987). A continuum range can be established between highly tacit to fully articulable knowledge, argues Winter, depending on the ease with which it can be communicated in a codified symbolic form. The degree of observability is related to the amount of knowledge that is disclosed by using the knowledge itself. The degree of complexity refers to the amount of information required to characterise an item of knowledge, that is, the number of alternative possibilities from which a particular case must be distinguished. The systemic nature reflects whether an item of knowledge is completely independent, and useful by itself, or is an element of an interdependent system and assumes significance and value only within that specific context. All these dimensions, concludes Winter (1987), affect the ease to transfer knowledge. On one extreme, knowledge that is tacit, not observable, complex and element of a broader system is difficult to transfer. On the other extreme, articulable, observable, simple and self-standing knowledge can be easily transferred. As these properties of knowledge are difficult to measure, Cohen and Levinthal (1990) proposed to study the importance for innovation in any firm or industry of different fields of knowledge, each one embodying certain (unmeasured) characteristics.

Section Three: A new typology of technological regimes

The identification of technological regimes relies on the properties of innovation processes and the nature of the underlying knowledge bases that characterise distinct sets of production activities. In the following discussion, sectors are identified which exemplify various technological regimes, and data on each sector, and on the technologies upon which sectors rely, are used to support the analysis of differences in regimes.

3.1. Data sources and statistical indicators

The knowledge base. The nature of the knowledge base is expressed by the relevance that various fields of knowledge (e.g. chemical, mechanical, electrical-electronic) assume for innovation in an industry. Empirical studies on the profile of firms' technological competencies have referred to the distribution across technological classes of various indicators of innovative activities such as R&D expenditure (Jaffe 1989), patenting (Jaffe 1986, Patel and Pavitt 1997), and technical and scientific personnel (Jacobsson and Oskarsson 1995). In this paper, the analysis relies on the SPRU data base of the world's largest firms. This database is composed of 539 firms from the *Fortune* list classified into 16 principal product groups according to their sector of principal product activity (Patel and Pavitt 1991, Patel and Pavitt 1997). Using this data set, the knowledge base that underlies innovation in an industry is expressed, in first approximation, by the distribution among 34 technical fields of the patents granted to large firms in any principal product group over the period 1981-90. In addition, the profile of technological competencies is also analysed on the basis of the distribution across occupational classes of scientists, engineers and technicians employed in US manufacturing industries in the year 1992 (NSF 1995a).

The level of technological opportunity. At the level of technologies, conditions of opportunity for innovation are described by using patent data from the US Patent Office classified in 34 technical fields according to the SPRU classification. In each field, the patent share over the total patenting activity in the period 1981-94 defines a measure of the general level of technological opportunity. Its long-term growth rate is also calculated with respect to the period 1969-80. As the data refer to the overall number of patents granted to firms, private individuals and public institutions, these indicators represent the general ease to innovate in a technology, and its long term variation, independently of which agents exploit new opportunities. At the level of industrial sectors, a measure of technological opportunity is defined that integrate indicators of innovative input with indicators of innovative output of firms, by using the SPRU database of the world's largest firms. In any principal product group, the following indicators are calculated: (i) the total intensity of R&D expenditure in the year 1988[2], (ii) the total percentage of patents in fast growing technologies in the period 1985-90[3], and (iii) the total patent intensity, proxied by the ratio of the number of patents in the period 1985-90, on the volume of sales in 1988. The sectoral pattern of technological opportunity that emerges for the leading firms is broadly consistent with classifications based on the intensity of R&D expenditure for the entire population of firms in an industry in OECD countries (STAN and ANBERD databases). In addition, a comparison was made for US firms between the intensity of R&D expenditure and the percentage of R&D personnel in any industry (NSF 1995b), comparison that revealed similar sectoral patterns. However, R&D statistics tend to underestimate the level of technological opportunity in product-engineering industries that are characterised by a large presence of small firms, typically non-electrical machinery. This problem is revealed by using innovation counts (Pavitt 1984) or by comparing R&D statistics with patent intensities in the set of the world's largest firms used in this analysis.

Technological entry barriers. Given the general level of technological opportunity in a field of knowledge, the ease of access to such opportunities by established firms with respect to new firms depends on the specificity of knowledge to industrial applications, the existence of scale- and in-house advantages in learning processes. Statistical indicators of these factors were defined by using patent data from the US Patent Office classified in 34 technical fields in the period 1981-90 (SPRU data source). Following Patel and Pavitt (1994), the Herfindhal index of concentration of the patent activities granted in an technical field to the world's largest firms across the 16 groups of principal product activity is used as a measure of the specificity of knowledge to industrial applications. In any technical field, the share of patents that are granted to

[2] Data on firm R&D intensity were available for a subset of 443 companies (Patel and Pavitt 1991).
[3] Fast growing technologies as the 1000 technologies, out of a total of around 100000, with the highest growth rates in patenting from the 1960s to the late 1980s (Patel and Pavitt 1997).

the world's largest firms is used as a proxy of scale advantages in learning processes. Lastly, it is assumed that the share of patents granted to private individuals is inversely related to the existence of in-house advantages in innovation. This is because private individuals are mainly represented by individual owners of very small firms, therefore with similar characteristics to new firms (Patel and Pavitt 1995). In order to build analogous indicators at the level of industrial sectors, the set of technologies that compose the knowledge base of the world's largest firms in any industry is considered. The average values of the indicators of the ease of access to opportunity for innovation across fields of knowledge, weighted by the patent shares in each one field of the firms in the sector, are used as measures of technological entry barriers at the level of principal product groups. Such indicators assume a linear contribution of each technology to the innovation process in a sector. They do not capture entry barriers that originate in the need for a firm to manage and co-ordinate an interdependent system of different fields of knowledge, even when such fields are individually easy to access.

In this analysis of regimes the focus is on technological entry barriers rather than on appropriability. Empirical studies of appropriability conditions based on surveys of R&D executives (Levin et al. 1987, Harabi 1995, Arundel et al. 1995) have revealed some general patterns. However, these studies have concentrated on the effectiveness (or not) of the patent systems compared to other instruments. They do not define an aggregate measure of appropriability or ease of imitation. Furthermore, when these studies focused on sectoral differences in the effectiveness of the various means of appropriability, they revealed significant difficulty in identifying homogenous clusters of industries that could be distinguished by significantly different levels of appropriability (Levin et al. 1987, Malerba and Orsenigo 1990). For example, Levin et al. (1987) have identified a cluster of industries in which no appropriation mechanism of the returns of innovation was particularly effective[4], but also noticed that not other regular pattern could be established.

Cumulativeness of learning. Empirical studies on the cumulativeness of learning are generally based on measures of persistence in firm innovation over time. Empirical evidence on the stability of innovation at the level of technologies can be drawn upon various studies based on patent statistics. They analyse the stability in the directions of search in fast growing fields by large firms (Patel and Pavitt 1997), the autocorrelation

[4] The low-appropriability cluster included food products and metalworking sectors, when product innovation was considered; it included the same industries and also fabricated metals and machinery, when process innovation was considered.

in the micro time series of patent activity (Cefis 1996), and the rank correlation over time in the hierarchy of innovators (Malerba and Orsenigo 1996). In order to define a proxy of stability in innovation at the level of industrial sectors, the SPRU data base on the world's largest firms is also used in the analysis. In particular, the Spearman rank correlation coefficient in the hierarchy of innovators, established according to the total number of patents, between the period 1969-74 and the period 1985-90 is calculated. Measurement problems affect the analysis of cumulativeness in learning processes when the analysis is based on indicators of stability in firm innovation. A first problem concerns the quite broad classification of technologies and products groups that are adopted in most studies. As a result, cumulativeness in the local processes of learning may not be accounted for, as Patel and Pavitt (1997) pointed it out. Another problem derives from the fact that indicators of persistence in innovation are partly measures of the size of innovating firms. In areas where large firms are the major actors, innovation may display high stability because statistical aggregation reduces variability.

Technological diversity. Measurements of inter-firm diversity in the level of technological activities are defined for the set of the world's largest firms within any principal product group. Intrasectoral technological diversity is measured by the coefficients of variation (ratio of standard deviation on average) among firms in their intensity of R&D expenditure in the year 1988, in their patent intensity in the period 1985-90, and in their share of patents in fast growing fields. These indicators of inter-firm diversity in the rate of knowledge accumulation are also compared with an indicator of inter-firm diversity in search directions that was calculated by Patel and Pavitt (1997) for the same set of firms. The indicator built by Patel and Pavitt uses the percentage of correlation coefficients between the patent shares profile of each firm with that of each other firm within the same sector, that are statistically significant (i.e. a measure of inter-firm homogeneity in knowledge base).

Technological diversification. The intensity and directions of technological diversification that characterise as a whole firms in any industry are examined by using the patent profile of the world's largest firms in any principal product group. The intensity of diversification of the knowledge base is inversely expressed by the Herfindhal index of concentration of patent activities across diverse technologies in any product group. As the Herfindhal index of concentration depends on both the number of considered technologies and the degree of dispersion among them, different criteria of technological classification are selected: five broad technical areas, 34 technical fields, and 91 subtechnical fields[5]. In principle, the diversification of the knowledge base may reflect firms' ability to exploit technological opportunities in related product markets, as well as the complexity of innovative processes. This last in turn may originate in different factors: the complexity of knowledge, the complexity of products, and the complexity of production processes. The analysis of the directions of technological diversification across core and background competencies (Granstrand, Patel and Pavitt 1997) makes it possible to account for the various sources of diversification of the knowledge base. In particular, a high degree of diversification of background competencies in production- related technologies reveals a complex supply chain (Granstrand, Patel and Pavitt 1997).

Sources of knowledge. Empirical studies on the conditions of opportunity and appropriability of innovation based on surveys of R&D executives in European and US industries have contributed to illustrating sectoral differences in the sources of knowledge for innovation (Levin et al. 1987, Klevorick et al. 1995, Arundel et al. 1995). For the European manufacturing firms in particular, data from the PACE survey available at level of industrial sectors (Arundel et al. 1995) are used in order to identify the sources which are distinctively important in any sector, in the context of an eventually complex system of external sources of knowledge. The same data source is used more specifically in order to assess the relevance of academic research for industrial innovation, in various fields of knowledge that are distinguished according to the areas of basic science, applied science, and engineering, and characterised in terms of their pervasiveness across industrial applications. A number of empirical studies have been accumulated that focus on the relevance of scientific advances in academic research as an external source of knowledge for industrial innovation. Some studies have stressed differences across technologies and sectors in the direct contribution of codified scientific findings of basic research performed to a large extent by academic institutions (Pavitt 1998), contribution measured by the frequency of citations to refereed journals in patent applications (Grupp 1996, Narin, Hamilton and Olivastro 1997). Other studies have used corporate publications and highlighted sectoral differences in the extent to which firms undertake in-house basic research (Hicks and Katz 1996) also in order to be able to monitor, understand and effectively exploit the outcomes of academic research (Cohen and Levinthal 1989). In addition, the relevance of in-house basic research is assessed in this analysis of regimes by using data on the distribution of R&D expenditure across basic research, applied research and

[5] The total patent profile at the level of 91 technical sub-fields was available for the period 1981-88.

development for US manufacturing industries in the year 1992 (NSF 1995). Such a distribution is also compared with the distribution of R&D personnel across scientists, technicians and engineers for the same set of industries (NSF 1995)

Lastly, it has to be considered that part of the knowledge transfer among industries is embodied in capital goods and intermediate products. The importance of sources of capital embodied knowledge in a sector is explored by using the matrix of inter-industry R&D expenditure flows in US manufacturing firms built up by Scherer (1982). By using these data a distinction is also made between product- and process-trajectories of technical change.

3.2. Description of regimes

A typology of technological regimes is proposed that distinguish the properties of innovative processes in science-based regimes, fundamental processes regime, complex (knowledge) systems regime, product engineering regime and continuous processes regime. The main traits of these regimes are summarised in Table 1 and the industries composing each regime are listed in Table 2. Industries within each regime are initially identified through a cluster analysis based on the total profile of technological competencies of firms in an industry, profile expressed by either the patent distribution or the personnel distribution across various fields of knowledge. These sets of industries share different knowledge bases at various levels of technological distance, and display divergent characteristics of learning processes and sources of knowledge.

Science-bases technological regimes characterise the pharmaceuticals and electrical-electronics industries. These regimes are distinguished by high technological opportunity, high technological entry barriers in knowledge and scale and high persistence of innovation. Firms are characterised by a low degree of diversity in the rates and directions of innovations and by a knowledge base, as a whole, rather concentrated on fields associated with horizontally related product markets and with upstream production technologies (this last direction is less pronounced in pharmaceuticals, however). Innovation benefits from external sources of knowledge such as public institutions and joint ventures, in particular. The contribution of academic research is important and direct, involving mainly unpervasive fields of scientific knowledge. Innovative activities are principally devoted to product innovation. The fundamental processes- regime characterises chemicals and petroleum industries. It presents similar characteristic to the preceding regime, but with relatively lower level of technological opportunity and of scientific inputs from academic research and other public institution. Innovation is mainly process innovation. The complex (knowledge) system regime is still characterised by medium-high levels of opportunity, entry barriers in knowledge and scale, and persistence of innovation. It characterises motor vehicles and aircraft industries. The distinctive feature of this regime is in the high degree of differentiation of technological competencies developed by firms, especially in upstream production technologies, and, as well, of the external sources of knowledge, including an important, despite indirect, contribution of academic research. The product-engineering regime is characterised by a fairly high level of opportunity, low entry barriers and not very high persistence of innovation. It includes in particular non-electrical machinery and instruments. Firms are highly heterogeneous in their rates and directions of innovation. The profile of technological competencies is rather differentiated in horizontally related products and in downstream products (e.g. transportation). Innovation, in products, benefits from the external contribution of knowledge, mainly, from users. Last, the continuous process regime presents low opportunity, low entry barriers and rather low persistence of innovation. Firms are technological heterogeneous and their knowledge base is, as a whole, rather differentiated upwards production technologies. Innovation, mainly in processes, benefits from upstream sources of capital-embodied knowledge.

As in any classificatory exercise, cases can be identified that share traits typical of different categories. In particular, industries within the continuous process regime show a certain degree of variability. The metals industry shares characteristics, such as the persistence of accumulation of core competencies and the complexity of production processes, common to other ‘scale-intensive’ industries (Pavitt 1984) that are classified within the complex system regime. Furthermore, the food and drink industries display a few traits typical of the life science based regime, such as closer links to science and a concentrated profile of technological competencies.

Table 1
Technological regimes in the industrial system

	Technological opportunity	Technological entry barriers in knowledge and scale	Persistence of innovation	Inter firm diversity	Differentiation of the know. base (main directions)	External sources of knowledge	Links with academic research (fields of knowledge)	Nature of innovation
Science-based	High	High (knowledge)	High	Low	Low (horizontal and upstream, less often in pharmac.)	Public institutions and joint ventures	Strong and direct (mainly unpervasive fields of knowledge)	Product
Fundamental processes	Medium	High (scale)	High	Medium	Low (horizontal and upstream)	Affiliated firms and Users	Quite important and direct (basic and applied science)	Process
Complex systems	Medium	Medium/High	High in technologies but not in products	Medium	High (upstream)	Complex system of sources	Quite important but indirect (engineering)	Product
Product engineering	Medium-high	Low	Medium-Low	High	High (horizontal and downstream)	Users	Not very important (pervasive mechanical engineering)	Product
Continuous processes	Low	Low	High in metallurgical technology but not in products (i.e. metals), and in build. materials Low in the others	High	High (upstream) Low in food, drink (upstream and horizontal)	Suppliers, esp. capital-embodied	Not very important (pervasive applied science i.e. metallurgy and materials) More important and direct in food (basic science)	Process

Table 2
Industries within technological regimes

Life science-based	Drugs and bioengineering
Physical science-based	Computers Electrical Telecommunications Instruments (Photography & photocopy)
Fundamental processes	Chemicals Mining & Petroleum
Complex systems	Motor vehicles Aircraft
Product engineering	Non electrical machinery Instruments (Machine controls, electrical and mechanical instruments) Fabricated metal products Rubber and plastic products Other manufacturing Household appliances
Continuous processes	Metallurgical process (Basic metals, Building materials) Chemical processes (Textiles, Paper and Wood) Food and Drink (Food, Drink and Tobacco)

Section Four: The fundamental properties of learning

This section analyses how the various dimensions of technological regimes relate one another leading to a few dominant patterns. The relationships between the properties of innovative processes are analysed at the level of technologies and products.

4.1. Technological opportunity and technological entry barriers by knowledge field

The relationship between the general level of technological opportunity and technological entry barriers is not known *a priori*. High opportunity to innovate in a technology may increase the innovative advantage of established firms that cumulatively innovate upon past successes. On the other hand, high technological opportunities may facilitate the innovative entry of external firms. In order to compare these two dimensions the correlation matrix of the indicators of technological opportunity and entry barriers previously defined in 34 technical fields has been calculated (Table 3).

Table 3
Elements of technological entry barriers and opportunity: correlation matrix in 34 technical fields (1981-90) (p-value in parentheses)

	Herfindhal	Share large firms	Share individuals	Patent share	Patent growth
Herfindhal	1	0.61 (0.000)	-0.48 (0.004)	-0.41 (0.015)	0.14 (0.451)
Share large firms		1	-0.92 (0.000)	-0.21 (0.233)	0.16 (0.363)
Share individuals			1	0.14 (0.451)	-0.13 (0.456)
Patent share				1	0.13 (0.450)
Patent growth					1

Note: author's elaboration from SPRU database

Table 3 shows that in a field of knowledge the general level of technological opportunity and its long- term growth rate are not significantly correlated to entry barriers that originate in scale and in-house advantages in innovation. General conditions of technological opportunity and technological entry barriers to new small firms represent two independent dimensions. High levels of technological opportunity characterise fields of knowledge where large established firms have an innovative advantages, such as computers and drugs, as well as those where new small firms are strongly innovative, such as non-electrical machinery and instruments. A negative and statistically significant correlation emerges between the level of technological opportunity and the degree of specificity to industrial applications of a field of knowledge. Pervasive fields of knowledge show high levels of technological opportunity as a whole. That is, fields of high technological opportunity represent important directions of technological diversification by established large firms. With respect to the indicators of technological opportunity, it also results that the total share of patents in a technical field and its long-term growth rate are not significantly correlated. The level of technological opportunity and its long-term rate of growth define two orthogonal dimensions in the properties of innovative processes in a field of knowledge.

4.2.   Fundamental factors by product group

While the previous conclusions refer to single fields of technological knowledge, by using the SPRU data base on the world's largest firms a comparison is also made between the dimensions of a technological regime across industrial sectors. In order to illustrate the relationships between the properties of innovative processes, a principal component analysis of the various statistical indicators has been carried out. The analysis produces three orthogonal common factors that cumulatively explain 56.4 %, 69.4% and 71.8 % of the total variability in the original variables. In order to define these factors, reference to their correlation coefficients with the initial variables is made (Table 4). In particular the coefficients of the first factor, that account for most variability of data, make it possible to evaluate the relationships between the original indicators used in the analysis[6]. The factor scores by principal product group are represented in Figure 1 and Figure 2. Of course, these graphs provide a low dimensional representation of more articulated combinations of the properties of technological regimes that were illustrated in Table 1.

Table 4
The fundamental dimensions of technological regimes: correlation matrix in 16 product groups

	Factor 1	Factor 2	Factor 3
Opportunity			
R&D intensity	**0.88**	-0.10	0.28
FG pat share	**0.75**	-0.31	0.09
Pat intensity	**0.68**	-0.42	-0.42
Barriers			
Herfindhal	**0.83**	-0.28	0.06
Large firms	**0.83**	-0.24	-0.14
Individuals	**-0.83**	-0.02	0.20
Diversity			
R&D diversity	**-0.78**	0.00	0.20
FG diversity	**-0.70**	0.41	-0.39
Pat diversity	**-0.77**	-0.05	0.26
PS homogeneity	**0.65**	0.19	**0.64**
Tech. concentration			
Herf 5	**0.75**	0.40	-0.19
Herf 34	**0.59**	**0.70**	-0.03
Herf 91	**0.66**	**0.66**	0.03
% Cumulated Var.	56.4	69.4	77.4

Note: author's elaboration from SPRU database

[6] Similar relationships to those summarised in table 4 were also obtained by calculating the correlation coefficients among the original indicators.

Figure 1
Technological opportunity conditions and complexity of the knowledge base

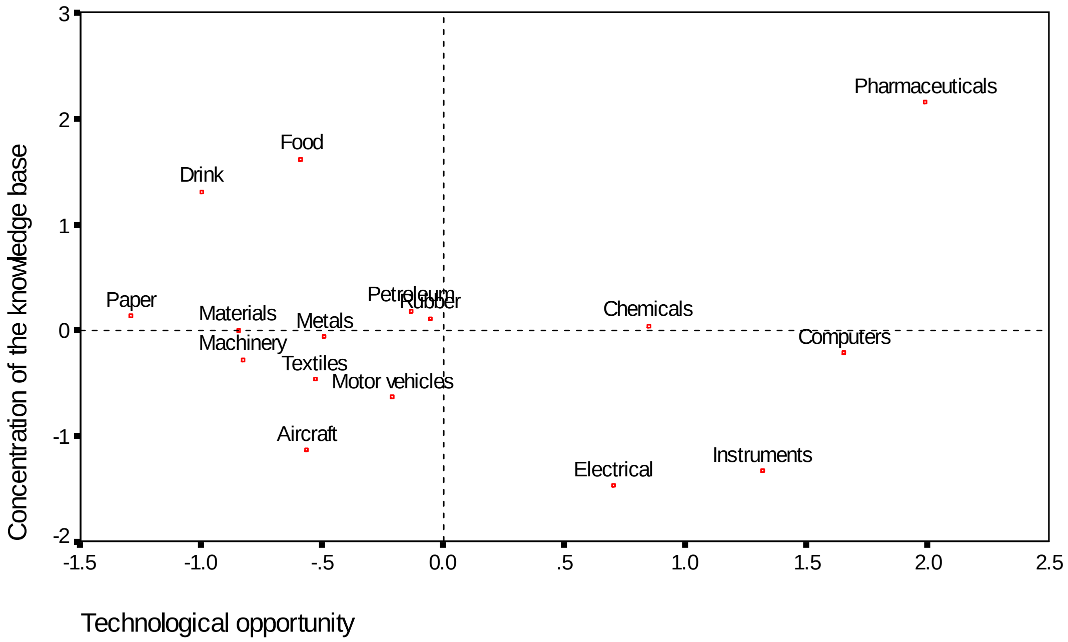
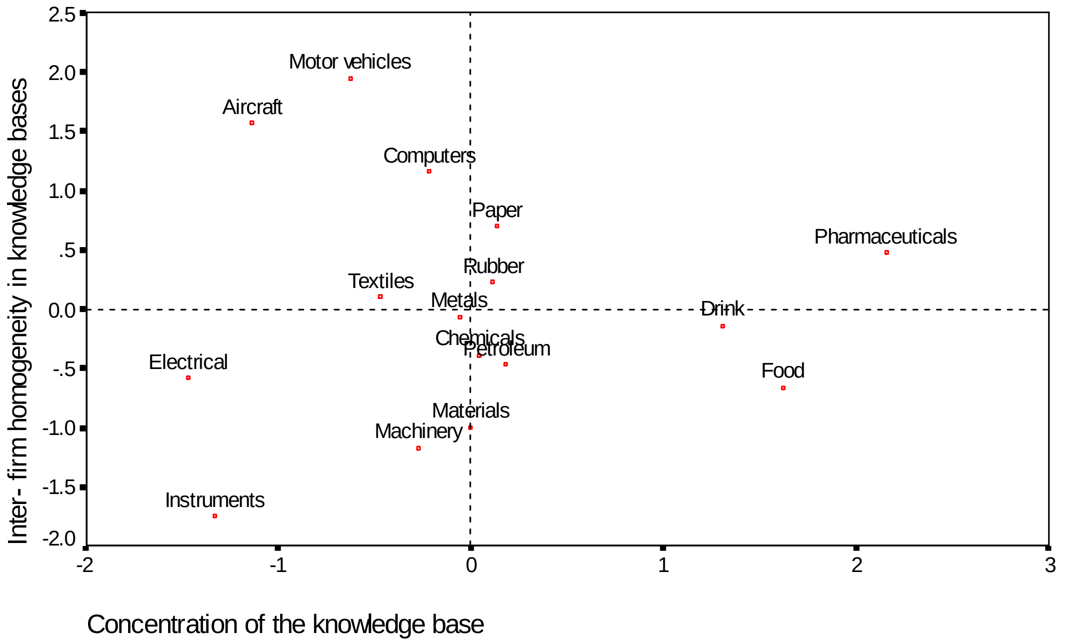


Figure 2
Complexity of the knowledge base and diversity of technological trajectories



4.2.1. Technological opportunity conditions

In Table 4, the first factor identifies those industries characterised by high technological opportunity of incumbents, high technological entry barriers, low inter- firm diversity and high concentration of technological competencies, especially within the same broad area of knowledge. It reflects the conditions of technological opportunity in terms of the specific ability of diverse firms, within and outside any industry, to exploit fields of high technological opportunity within a broad area of knowledge. Such factor, represented by the x-axis in Figure 1, distinguishes the science- based regimes.

It is worth noting that in Figure 1, the instruments product group shows conditions of high technological opportunity and high technological entry barriers, typical of the science based regime. Such a high level of technological entry barriers in the instruments sector is unexpected. In order to interpret this outcome one has to refer to the nature of the data and classification used. In the SPRU database of large firms, the instruments product group includes mainly firms in the photography and photocopy industry. In the typology of regimes introduced in table 1, a distinction is made, within the instruments sector at two-digit SIC code, between the photography and photocopy industry and the instruments industry (i.e. machine controls, electrical and mechanical instruments). The photography and photocopy industry is classified within the science-based regime. The instruments industry is characterised by a product-engineering regime with high technological opportunity and low technological entry barriers. Industries within the broad instruments sector display similar high levels of technological opportunity, for example illustrated by the intensity of R&D expenditure in US manufacturing industries at the level of four-digit SIC code (Toulan 1996). However, different patterns within the sector emerge in the pervasiveness of knowledge across industrial applications and consequently in the strength of technological entry barriers. In particular, the analysis of patent statistics revealed that the photography and photocopy technology is characterised by high entry barriers to innovation, showing a pattern similar to the electrical/electronic group. Conversely, entry barriers to innovation were low in instruments and machine controls technologies, more similarly resembling the non-electrical machinery area of knowledge.

The empirical evidence summarised by the technological opportunity factor does not support the hypothesis that search processes in fields of emerging technological opportunity are the major sources of diversification of firm competencies. Conversely, areas of high technological opportunity, in terms of fast growing patenting fields, are associated with high concentration of the range of technological fields in which firms are active, especially within the same broad area of knowledge. The measure of diversification of the knowledge base used in the analysis relies on the total profile of technological competencies by firms in an industry. Therefore it may be biased in presence of high inter-firm diversity of the knowledge base. Yet, the results are consistent with empirical studies based on the patent profiles of individual firms. Granstrand, Patel and Pavitt (1997) drawing a comparison between three companies, observed the highest degree of technological diversification in the automobile company, followed by the electrical/electronic company, while the chemical company was the least technologically diversified. Prencipe (1997) found a wide spread of technological competencies internally developed by aero-engine companies, and Laestadius (1998) noted that high diversification of technological competencies characterises low-tech industries such as the paper and wood industry, in which firms develop significant competencies in chemical, mechanical and software technologies.

In the pattern shown by the technological opportunity factor, no empirical support is also found to the assumption that inter-firm diversity in innovative process leads to high opportunity for innovation as firms can explore a variety of technical solutions. Conversely, it emerges that 'technological imperatives' imposed by the nature of technologies upon the innovative behaviour of leading firms are stronger in areas of high technological opportunity, typically in science-based regimes. In order to assess the relationship between technological opportunity and variety a distinction is to be made between diversity and asymmetries in firm innovation (Dosi 1988). The indicators used in this analysis refer to inter-firm diversity in innovative behaviour (e.g. R&D intensity) and innovative output (e.g. patent share in fast growing technologies). However, it does not allow to distinguishing the component of asymmetries in the innovative performance of firms that undertake similar innovation strategies. Such asymmetries originate in the partly random nature of search and are expectedly associated with high opportunity for innovation (Nelson and Winter 1982).

4.2.2. Complexity of the knowledge base

High diversification of the knowledge base is related to the complexity of products and/or production processes. This property is illustrated by the second factor identified in a regime. This factor is independent on the previous one and is determined by the degree of concentration of the knowledge base particularly across single technological fields (Table 4). This factor is represented by the y-axis in Figure 1. Among industries with generally low levels of technological diversification in the I and IV quadrants, it distinguishes the life-science based regime from the physical-science based regime, being the latter characterised by a relatively higher level of diversification among technologies within the same broad area of knowledge than the former. Among industries with generally high levels of technological diversification of the knowledge base in the II and III quadrants, the factor distinguishes the complex system regime for its particularly high level of technological diversification both within and across distant areas of knowledge, with respect to the continuous processes- regime. In turn, within the latter regime, the food and drink industries are characterised by high concentration of the knowledge base in technologies that yet belong to distant areas of knowledge.

The empirical evidence summarised in Figure 1 thus would suggest that processes of technological diversification related to the exploration of emerging technological opportunities involve mainly ‘close’ fields of knowledge, as it is illustrated by the physical-science based regime. Conversely, in industries characterised by significant complexity in products and/or production processes, firms are technologically active in a wide range of ‘distant’ fields of knowledge, independently on the conditions of technological opportunity. The complexity factor identifies an additional source of technological entry barriers in the need to co-ordinate and to integrate diverse fields of knowledge, independent of the ease of innovating in each individual field by new and established firms. Such factor in particular, argued Winter (1987), influences the ‘actual’ decision of innovative entry, for given conditions of potential entry that are determined by the exposure of different agents to the same knowledge base.

4.2.3 Diversity of technological trajectories

The degree of inter-firm diversity in knowledge base identifies a third orthogonal factor in a regime (Table 4). This factor shows that in industries where high technological opportunities originate especially in product engineering and design rather than in R&D activities, high levels of inter-firm diversity in search directions may coexist with significant homogeneity in their levels of technological activity. By comparing this evidence with that summarised by technological opportunity factor, it can be concluded that technological imperatives associated with conditions of high opportunity of innovation act, in particular, upon the innovative effort and capability of firms, while are relatively less strong upon their technological trajectories. In Figure 2 this factor is represented by the y-axis in comparison with the factor of complexity of the knowledge base previously discussed. In the I and IV quadrants, it distinguishes the life science based regime in which firms are active in few technical fields along similar search trajectories, from the food and drink industries in which firms are active in few technical fields but along distinct trajectories. In the II and III quadrants, this factor distinguishes between the complex system regime and non-electrical machinery typical of the product-engineering regime. In the complex system regime firms are active in a wide range of technical fields along similar search trajectories but with a certain variety in their ability to exploit technological opportunities strongly related to R&D activities. In non-electrical machinery, firms are active in a wide range of technical fields along distinct search trajectories but with homogeneity in their ability to exploit technological opportunities, mainly associated with patent activities.

High technological opportunities can thus be related to low diversity in both levels of technological activities and search trajectories of firms, as in science based regimes. However, in sectors where high technological opportunities originate especially in product-engineering, firms appear to undertake similarly intense and successful processes of learning along diverse technological trajectories, as result of the '*product richness*' of the capital goods sector. The diversity of technological trajectories in a regime represents another fundamental factor that influences technological entry barriers in an industry. As suggested by Malerba and Orsenigo (1990) technological diversity among firms within an industry is expected to reduce the strength of entry barriers to innovation, as external firms can experiment with different technical solutions. Such consideration would confirm the possibility of having in an industry simultaneous conditions of high technological opportunity and low technological entry barriers that originate not only in the pervasiveness of knowledge across production activities, but also in the diversity of technological trajectories that firms may explore.

In Figure 2, the comparison between inter-firm diversity in the knowledge base and the diversification of the knowledge base in an industry makes it possible to identify possible sources of biases in the aggregate measure of technological diversification used in the analysis. Figure 2 shows that among sectors with high diversification of the total profile of technological competencies, non-electrical machinery is characterised by high inter-firm heterogeneity of the individual profiles. At this level of analysis, it is not possible to distinguish whether such diversification of the knowledge base as a whole is the outcome of the variety of search trajectories of firms that specialise in different product markets or of internal processes of horizontal diversification. An opposite pattern characterises the complex system regime in which high levels of differentiation of the knowledge base as a whole, being associated with high inter-firm homogeneity of the knowledge bases, derive essentially from internal processes of technological diversification by individual firms.

Al a lower level of variability than that across regimes, the original variables summarised in Figures 1 and 2 show that a pattern similar to the complex system regime also distinguishes the metals industry within the continuous processes regime. In this industry, the diversification of the knowledge base is particularly high, especially taking into account the significant homogeneity in knowledge bases among individual firms. The metals industry appears to be characterised by a rather complex supply chain, also in comparison with other industries in the same regime.

4.2.4 Persistence of innovation

The factors previously identified can also be compared with a statistical proxy of the stability in the hierarchy of innovators in a principal product group, for the same set of firms (Table 5). Although the persistence in the hierarchy of large innovators is statistically significant in most cases, differences are noticeable among product groups[7].

Table 5
Persistence of patent activity of the world's largest firms from 1969-74 to 1985-90

Industry	Spearman rank correlation	p-value	firms number
Mining and Petroleum	0.86	0.000	41
Building Materials	0.85	0.000	24
Chemicals	0.82	0.000	71
Food	0.80	0.000	37
Computers	0.80	0.000	17
Pharmaceuticals	0.73	0.000	25
Motor Vehicles	0.73	0.000	41
Electrical-electronic	0.67	0.000	58
Instruments (Photo&C)	0.67	0.001	21
Paper and Wood	0.62	0.000	31
Metals	0.58	0.000	49
Aircraft	0.57	0.010	19
Machinery	0.56	0.000	62
Textiles etc.	0.51	0.052	15
Drink & Tobacco	0.44	0.104	15
Rubber & Plastics	0.35	0.356	9
Total manufacturing	0.78	0.000	539

Source: author's elaboration from SPRU database

Empirical studies on the stability of search directions (Patel and Pavitt 1997) and levels of technological activity (Cefis 1996) have compared broad technological classes. These studies generally display the highest degree of stability in the chemical technology; the electrical-electronic technology and the transport technology at a similar level of stability follow this. Innovation in the instruments technology is less persistent than electrical-electronics but more persistent than non-electrical machinery. The lowest level of stability is observed in 'other' technologies. Malerba and Orsenigo (1996) found similar patterns by considering stability in the level of firm innovative activity at a more disaggregated level of technological classification. Their findings show that within electrical/electronic technologies, generally highly stable, lower levels

[7] A principal component analysis was also applied to all the indicators used in the study of technological regimes in the world's largest firms. The measure of persistence of innovation identifies an additional factor to those represented in Table 4.

of persistence distinguish consumer electronics and household appliances, with a pattern resembling mechanical technologies. A rather differentiated pattern emerge within chemical technologies as chemical processes, inorganic chemicals, and agricultural chemicals show much lower persistence than organic chemicals, hydrocarbons, drugs and bioengineering. Last, high degrees of persistence characterise metallurgy and new materials technologies.

In short, the empirical evidence shows that innovation is especially stable in fundamental processes industries (chemicals and petroleum) in the overall level of technological activity of firms as well as in the accumulation of core technologies. In some industries characterised by a rather complex base of knowledge, such as aircraft and metals industries, high stability in the accumulation of core competencies (in aircraft and metallurgy respectively) seem to coexist with a certain instability in the overall levels of technological activity of major firms. Such outcome reflects the more volatile patterns characterising innovation in background production technologies, such as non-electrical machinery, typical of these industries. An opposite pattern is observed in the food industry in which large firms display high stability in the overall level of technological activity, although volatile patterns of innovation characterise more generally firms active in food technologies (Malerba and Orsenigo 1996).

The degree of persistence in the hierarchy of large innovators in a product group is positively correlated to the strength of technological entry barriers. The correlation is not statistically significant with the level of technological opportunity, and the other dimensions of a technological regime though. Similarly, Malerba and Orsenigo (1996) found that the stability in the hierarchy of innovators is negatively related to the rate of innovative entry across technologies. The positive relationships between technological entry barriers and persistence of innovation may originate in two factors. First, technological entry barriers related to the scale of production may endogenously emerge as outcome of highly cumulative processes of learning. Second, indicators of persistence in innovation do not disentangle the spurious effect of firm size, effect that reduces volatility because of aggregation. Despite measurement limitations, the empirical evidence would suggest that the cumulativeness of learning represents another dimension of a regime, independently on the level of technological opportunity.

The previous analysis also hints that it is important to distinguish between technologies and products in order to assess the cumulativeness of learning processes. Differences in stability may exist between core and background competencies that are relevant for innovation in a certain production activity. Furthermore, when innovation relays on a complex set of technologies, discontinuities at level of products may originate in integrating diverse fields of knowledge, each one of them characterised eventually by strong cumulativeness of learning. In this respect, more empirical investigation of the profile of technological competencies of firms active in an industry is required.

Section Five: Conclusions

The paper provides a first systematic synthesis of the empirical evidence on the characteristics of innovation across industrial sectors. For this goal, taxonomic exercises of industries were carried out on the basis of a combination of indicators of firm technological activities (e.g. patent, R&D, scientific input) derived from various data sources. The empirical analysis of innovative activities across industries, which lead to the identification of regimes, also highlighted more general conclusions on technological change. These conclusions are important in order to interpret cross-sectors differences in the dynamics of industrial competition. In particular, the paper questions existing assumptions about the variables underlying industrial dynamics. It argues that the two concepts of barriers to imitation (or appropriability of innovation) and barriers to entry via innovation need to be distinguished in order to understand the determinants of industrial competition. Technological entry barriers in an industry are important as influence the ability of external firms to exploit new technological opportunities and enter the industry.

Technological entry barriers originate in the nature of knowledge relevant for firm innovation such as the specificity to industrial applications and cumulativeness, this last factor in particular being intertwined with scale related advantages in learning processes. The ease of access to innovation by external firms is independent on the general level of opportunity for innovation in a field of knowledge. However, high technological entry barriers are associated with high levels of technological opportunity for leading firms in terms of their ability to exploit fields of increasing opportunities that originate in high R&D intensities and direct links with academic research.

The paper also focused on the relationship between technological opportunity and variety. In the analysis of technological variety among firms two elements need being distinguished: (ii) the existence of asymmetries in innovative performance among firms undertaking similar innovative processes (i.e. with the same technical coefficients) and (ii) the existence of diversity in innovative strategies and search trajectories. The paper addressed this second factor, as an empirical analysis of the first factor would require a much lower levels of aggregation. The analysis showed that the exploitation of areas of increasing technological opportunity by leading firms imposes strong technological imperatives upon firm innovative strategies and search directions along rather focused trajectories. That is, technological opportunities are associated with more, rather than less, technological diversity among firms.

Lastly, the paper argued that although conditions of technological opportunity, technological entry barriers, and cumulativeness of learning in a field of knowledge are important to define regimes, other essential dimensions are to be considered when the distinction between technologies and products is taken into account. These dimensions are to a certain extent independent on the previous ones. They consist in (i) the complexity of the knowledge base that is produced internally and externally to a firm and (ii) the diversity of technological trajectories coexisting within a regime. Both factors, it is argued, influence the overall level of technological entry barriers in a sector, and therefore the dynamic patterns of industrial competition.

The empirical analysis of technological regimes has important implications for the theory of industrial organisation. Technological regimes define a linking mechanism between empirical evidence and theory. They provide an analytical framework that summarises the empirical evidence on the microeconomic dynamics of innovation. Formal models of economic systems can then be built that embody the general properties of innovation in alternative regimes (Nelson and Winter 1982, Dosi et al. 1995). Such models can be used as interpretative tools of the relationships between technological change and industrial dynamics according to a *bottom-up* approach. In particular, interpreting in evolutionary terms the contribution of Sutton (1998), technological regimes would identify ‘bounds’ to the patterns of industrial structures and dynamics that can be observed across sectors.

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