Technological regimes, patterns of innovative activities and industrial dynamics

A survey of empirical evidence and of some theoretical models

Luigi ORSENIGO

Cahiers d'économie et sociologie rurales, n° 37, 1995

Luigi ORSENIGO*

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Summary – *The paper surveys some results of empirical and theoretical analyses suggesting that the notion of technological regimes (as a proxy of the more general concept of learning regimes) may be a fruitful concept for studying the different ways in which technological progress and industries are organized and evolve over time. In particular, in an evolutionary perspective, the view is proposed that some stylized facts about the patterns of industrial dynamics and the patterns of technological change can be explained as the outcome of different selection and learning regimes that are implied by the nature of technology.*

The first part of the paper reports some results of empirical analysis on the patterns of innovation and industrial dynamics. First, some empirical evidence on the patterns of innovation is discussed, showing that substantial differences characterize the patterns of innovative activities across sectors, but remarkable similarities can be observed across countries in the same sectors. Against this background, it is suggested that one can meaningfully identify two basic groups of technologies in which innovation proceeds in quite distinct ways. One group resembles the "Schumpeter Mark I" model. The second group is more akin to the "Schumpeter Mark II" model. Subsequently, some major finding and puzzles which characterize industrial dynamics are discussed: patterns of entry and exit, persistence of firms' performances, stability of skewed distribution of firms' size.

The second part of the paper suggests some possible interpretation for these phenomena. The concept of technological regime is introduced and it is argued that this can be used fruitfully to provide a framework for analyzing firms' strategies and forms of organization as well as the sectoral patterns of innovative activities. Then, indirect and direct empirical evidence linking technological regimes to the sectoral patterns of innovation and industrial dynamics is reported. Finally, the paper briefly surveys some theoretical models in the evolutionnary tradition aiming at explaining and "generating" the observed empirical evidence.

Key-words:
patterns of innovation, technological regimes, industrial dynamics, evolutionary models

Régimes technologiques, modèles d'activités innovantes et dynamique industrielle. Revue des résultats empiriques et de quelques modèles théoriques

Résumé – L'article** passe en revue les résultats d'études théoriques et empiriques qui mettent en évidence l'utilité du concept de *régime technologique* (considéré comme une approximation du concept plus général de régime d'apprentissage) pour l'étude des différentes façons dont le progrès technique et les industries sont structurés et évoluent au cours du temps. Plus précisément, se situant dans une perspective évolutionniste, l'auteur propose de considérer les faits stylisés décrivant d'une part les modèles de dynamique industrielle, et de l'autre les modèles de changement technologique comme le produit des différents régimes de sélection et d'apprentissage imposés par la nature même de la technologie.

La première partie de l'article présente les résultats d'analyses empiriques menées sur les modèles d'innovation et de dynamique industrielle. Tout d'abord, des recherches portant sur les modèles d'innovation montrent qu'il existe des différences importantes entre ces modèles selon le secteur concerné, mais que l'on retrouve des situations analogues pour un même secteur dans différents pays. Sur cette base, les technologies peuvent être réparties en deux groupes dont les processus d'innovation sont tout à fait différents. Le premier groupe correspond au modèle Schumpeter Mark I. Le second s'apparente au modèle Schumpeter Mark II. Sont ensuite présentés les résultats et les questions caractérisant la dynamique industrielle : modèles d'entrées et sorties, persistance des résultas obtenus par les entreprises, stabilité de la distribution dissymétrique des tailles d'entreprises.

La seconde partie de l'article propose quelques interprétations possibles de ces phénomènes. L'auteur introduit le concept de régime technologique et montre l'intérêt qu'il présente, aussi bien pour l'analyse des stratégies d'entreprises et des formes d'organisation que pour les modèles sectoriels d'activités innovantes. Puis il présente des résultats empiriques directs et indirects reliant les régimes technologiques aux modèles sectoriels d'innovation et de dynamique industrielle. L'article se termine par une présentation rapide de quelques modèles théoriques du courant évolutionniste visant à expliquer et à "générer" les résultats empiriques observés.

Mots-clés:
modèle d'innovation, régime technologique, dynamique industrielle, modèle évolutionniste

* *Department of Economics, Bocconi University, via Gobbi, 5, 20136 Milano, Italy.*

** *Il reprend le texte de la conférence prononcée par l'auteur à l'Ecole-chercheurs du Col de Porte, Grenoble, le 6 avril 1995.*

THIS paper concerns the relationships between the observed patterns of innovative activities and evolution of industry structures on the one hand and the underlying microeconomic processes that might account for them [1]. Specifically, the paper surveys some results of empirical and theoretical analyses suggesting that the notion of **technological regimes** (as a proxy of the more general concept of learning regimes) may be a fruitful concept for studying the different ways in which technological progress and industries are organized and evolve over time.

In particular, available empirical evidence on these phenomena suggests a puzzling coexistence between variety, stability and change. One may start from the naive observation of high degrees of diversity in firms technological capabilities, organization, strategies and ultimately efficiency, both across and within industries. Together with this diversity, one observes also significant changes. Technological progress is a major engine of change and is ubiquitous. Many firms enter a sector in a given period of time and many other exit it. The ranking of the largest (or more profitable) firms companies changes significantly over time. Growth, stagnation and decline of firms – more generally, turbulence – appear to be a fundamental feature of industrial evolution.

Coexisting with variety and change, however, industrial evolution appears to be characterized also by remarkable degrees of persistence. This is particularly evident in the case of innovative activities, but also differentials in profitability among firms tend to persist over time. At the same time, some aggregate regularities, such as invariant skewed distributions of firm sizes, may be observed.

Finally, large and significant intersectoral differences in the degrees of variety and persistence are seen. In some sectors, diversity is more pronounced than in others. In some cases, technological change derives from the activities of a few large companies that innovate systematically over time, whilst in others new small companies play a significant role in the generation of technical progress. The degree of market share volatility, the persistence of performances and the role of small firms also widely differ across industries.

In recent years, evolutionary analysis of industrial dynamics has started to build an interpretation of the available evidence. In a nutshell, the evolutionary approach tries to provide some substance to the contention that market structures are endogenous to the processes of industry evolution and have to be explained as the outcome of evolutionary processes of learning and selection (Dosi and Orsenigo, 1988).

(1) This paper draws substantially on earlier works with Giovanni Dosi and Franco Malerba. They are not responsible, however, for any mistakes or omissions present in this draft. Support from the Italian National Research Council (CNR) (contract n° 94.02158.CT10-115.28709) is gratefully acknowledged.

In particular, in this paper the view is proposed that both the stylized facts mentioned above and the sectoral variety can be explained as the outcome of different selection and learning regimes that are implied by the nature of technology. In this respect, the notion of technological regime provides a synthetic representation of some of the most important economic properties of technologies and of the characteristics of the learning processes that are involved in innovative activities.

The paper is organized as follows. The first part of the paper reports some results of empirical analysis on the patterns of innovation and industrial dynamics. First, some empirical evidence on the patterns of innovation is discussed, showing that substantial differences characterize the patterns of innovative activities across sectors, but remarkable similarities can be observed across countries in the same sectors. Against this background, it is suggested that one can meaningfully identify two basic groups of technologies (sectors), in which innovation proceeds in quite distinct ways. One group resembles the "Schumpeter Mark I" (or creative destruction) model. The second group is more akin to the Schumpeter Mark II (creative accumulation) model (Section 1). Subsequently, Section 2 discusses briefly some major finding and puzzles which characterize industrial dynamics: patterns of entry and exit, persistence of firms performances, stability of skewed distributions of firms' size.

The second part of the paper suggests some possible interpretation for these phenomena. In section 3, the concept of technological regime is introduced and it is argued that this can be used fruitfully to provide a framework for analyzing firms strategies and forms of organization as well as the sectoral patterns of innovative activities. Thus, indirect and direct empirical evidence linking technological regimes to the sectoral patterns of innovation and industrial dynamics is reported. Finally, in the last section, the paper briefly surveys some theoretical models in the evolutionary tradition aiming at explaining and "generating" the observed empirical evidence.

As a survey paper, the paper does not present directly all the data, empirical analyses and models that support the argument advanced here. Moroever, the inclusion of tables and detailed descriptions of methodologies and models would have made the paper far too long. Thus, the paper simply reports the main results and the methodologies used to derive them, obviously indicating the original sources to which readers can refer.

SECTORAL PATTERNS OF INNOVATIVE ACTIVITIES: THE EMPIRICAL EVIDENCE

Schumpeter Mark I and Schumpeter Mark II

The ways innovative activities take place in industries and technologies may be quite different. One may find that in certain technologies innovative activities are concentrated among few major innovators while in others innovative activities are distributed among several firms. In certain technologies large firms do the bulk of innovative activities while in other small firms are quite active. Finally, in other technologies new innovators continuously appear while in others only established firms innovate; and so on.

This difference in the structure of innovative activities may be related to a fundamental distinction between Schumpeter Mark I and Schumpeter Mark II technologies. Schumpeter identified two major patterns of innovative activities. The first one, labelled by Nelson and Winter (1982) and Kamien and Schwartz (1982) Schumpeter Mark I, was proposed in *The Theory of Economic Development* (1912). This pattern of innovative activity is characterized by "creative destruction" with technological ease of entry and a major role played by entrepreneurs and new firms in innovative activities. The second one, labelled Schumpeter Mark II, was proposed in *Capitalism, Socialism and Democracy* (1942). In this work Schumpeter discussed the relevance of the industrial R&D laboratory for technological innovation and the key role of large firms. This pattern of innovative activity is characterized by "creative accumulation" with the prevalence of large established firms and the presence of relevant barriers to entry for new innovators. The Schumpeterian Mark I and Mark II patterns of innovation could be labelled also widening and deepening. A widening pattern of innovative activities is related to an innovative base which is continuously enlarging through the entry of new innovators and to the erosion of the competitive and technological advantages of the established firms. A deepening pattern of innovation, on the contrary, is related to the dominance of few firms which are continuously innovative through the accumulation over time of technological and innovative capabilities (Malerba and Orsenigo, 1995)[(2)].

(2) During the last forty years this characterization of innovative activities by Schumpeter has encouraged different scholarly traditions aiming at the empirical verification of the two patterns. The first, and oldest, tradition was mainly centered on the firm. It attempted to assess the role of firm size and of monopoly power in innovation (Kamien and Schwartz, 1982). The inconclusive results obtained in these empirical analyses are due to the neglected role of opportunity and appropriability conditions in the various industries (Levin, Cohen and Mowery, 1985) and of the endogenous relationship between firm size, concentration and technological change (Nelson and Winter, 1982). A second, and more recent, tradition has considered Schumpeter Mark I and II models according to the specific stage of an industry life cycle. According to the industry life cycle view, early in the history of an industry, when technology is changing very rapidly, uncertainty is very high and barriers to entry very low, new firms are the major innovators and are the key elements in industrial dynamics. On the contrary, when the industry develops and eventually matures and technological change follows well defined trajectories, economies of scale, learning curves, barriers to entry and financial resources become important in the competitive process. Thus, large firms with monopolistic power come to the forefront of the innovation process (Utterback and Abernathy, 1975, Gort and Klepper, 1982, Klepper, 1992).

However, very little is known about the empirical relevance of these two characterizations of technological change. There are different questions at stake here: first, is it possible to observe in the data patterns of innovation that more closely resemble the Schumpeter Mark I or the Schumpeter Mark II model? Second, what are the determinants of the different observed patterns of innovative activities?

Malerba and Orsenigo, in a series of papers, have begun to examine these issues in some detail, using patent data. First, the OTAF-SPRU data base on patents granted has been elaborated at the firm level for four European countries (Germany, France, the United Kingdom and Italy), for the period 1969-86 and considering 33 technological classes (Malerba and Orsenigo, 1995). Second, a similar analysis has been performed using a different dataset: the EPO data on patent applications for six countries (Germany, France, the United Kingdom, Italy, United States and Japan) in the period 1978-91 (Malerba and Orsenigo, 1996). Patent data have been aggregated into 48 main technological classes and one residual class. These classes have been built from 12-digit subclasses of the International Patent Classification (IPC) grouping them according to the specific application of patents. For each country, the whole population of firms applying for patents has been analyzed. Moroever, economic data have been gathered on firm's size in term of employees in 1984 as the OTAF-SPRU data are concerned and in 1991 in the case of EPO data[(3)]. The two datasets give remarkably consistent results. Thus, for sake of simplicity, in what follows reference will be made only to the EPO data.

Patterns of innovative activities have been analyzed on the basis of a set of indicators which attempt to capture some of the essential features of the two Schumpeterian "models". Specifically, Malerba and Orsenigo developed measures of the following characteristics of innovative activities:

i) Concentration and asymmetries among firms of innovative activities;
ii) Size of the innovating firms;
iii) Change over time in the hierarchy of innovators;
iv) Relevance of new innovators as compared to established ones.

[(3)] As far as the United States are concerned, 133,475 patents and 11,476 firms have been considered; for Germany 108,118 patents and 8,495 firms; for France 43,986 patents and 5,671 firms; for the United Kingdom 35,175 patents and 6,055 firms and for Italy 15,175 patents and 3,803 firms; for Japan 81,217 and 3,990 firms. In addition, for the four European countries data on the size of the innovators has been gathered: 56% of the German firms, 49% of the French firms, 34% of the British firms and 51% of the Italian firms have been covered. Firms part of business groups have been treated in the present analysis as individual companies. For details about the construction of the datasets, see Malerba and Orsenigo, 1996.

The first two sets of indicators (concentration and firm size) have been conventionally used in the traditional discussions of the Schumpeterian hypotheses. Clearly, they are meant to measure the extent to which innovative activities tend to be concentrated in few firms or are evenly distributed across a large number of firms and whether large firms or small firms are the main source of innovation in any particular technological class. The other two sets of measures aim to shed light on the degree of "stability" and "creative accumulation" or "dynamism" and "creative destruction" in the organization of innovative activity. In particular, these indicators try to identify dimensions related to the following questions:

- is the list of yesterday's main innovators the same as today's list or have other firms become more innovative?
- how relevant are new innovators as compared to old ones?

Thus, for each of the technological classes the following indicators have been constructed using patent data:

– **Concentration of Innovative Activities**: Concentration is measured by the concentration ratio of the top 4 innovators (C4). C4 is quite high in sectors such organic chemicals, macromolecular compounds, agricultural chemicals, aircraft, computers, telecommunications and nuclear technology. It is low in clothing, furniture, agriculture, mining, chemical apparatus, industrial automation, industrial machinery and equipment, civil engineering, mechanical engineering and measuring equipment. Moreover, we calculated the Herfindahl index ((HERF) to measure how symmetric or asymmetric is the distribution of innovative activities among firms. HERF is high for organic chemicals and macromolecular compounds, miscellaneous chemical compounds, electronic components and telecommunications while it is low for clothing, furnitures, agriculture, mining, metallurgy, industrial automation, industrial machinery, material handling apparatus, civil engineering, mechanical engineering, mechanical and electric technologies and sports.

– **Size of the innovating firms**: this is calculated simply as the share of total patent applications applied for by firms with more than 500 employees (SIZE). SIZE is high in inorganic chemicals, organic chemicals, macromolecular compounds, adhesives, agricultural chemicals, computers and other office equipment, while it is low in clothing, furnitures, agriculture and sports.

– **Stability in the hierarchy of innovators**: stability is measured by the Spearman rank correlation coefficient between firms innovating in 1978-85 and firms innovating in 1986-91 (SPEATOT). SPEATOT is low for clothing, furniture, agriculture, chemical processes, machine tools, industrial automation, civil engineering and sports, while it is high for gas and oil, organic chemicals, macromolecular compounds, new materials, adhesives, drugs, aircraft, electronic components and telecommunications. Malerba and Orsenigo (1994 and 1996) computed also a measure of the stability of the hierarchy of only those firms which innovate continuously over time (Spearman rank correlation coefficient between the hierachies of firms innovating in 1978-85 and 1986-91 (SPEACORE). The difference between SPEATOT and SPEACORE is that the first indicator considers also firms entering and exiting from the population of innovators. Thus, when turbulence is generated by new entrants and exiters but incumbent firms maintain over time a stable ranking, one might observe technological classes characterized by high values of SPEACORE but low values of SPEATOT. SPEACORE has a low positive value or a negative value in furniture, agriculture, mining, agricultural chemicals, chemical processes and machine tools, while it has a high positive value in organic chemicals, macro compounds, computers and office equipment.

– **Technological entry**: the relevance of new innovators is measured by the share of patent applications by firms applying for the first time in a given technological class in the period 1986-91 over the total number of patents in the same period (ENTRY). It must be noted that this indicator measures innovative entry and not entrepreneurial birth: a new innovator may in fact have been around for quite a long time. ENTRY is low for organic chemicals, macromolecular compounds, electronic components, consumer electronics and telecommunications while it is high for clothing, furniture, agriculture, mining, chemical processes, machine tools, civil engineering, lighting systems and sports.

Patterns of innovations are technology-specific

Schumpeterian patterns of innovation may be identified by the existence of specific and systematic relationships between these measures. In particular, the Schumpeter Mark I (widening) model should be characterized by low concentration and asymmetries in innovative activities, low stability in the ranking of innovators and high entry of new innovators and small size of innovators. Conversely, the Schumpeter Mark II (deepening) model should be characterized by high concentration and asymmetries in innovative activities, high stability of the hierarchy of innovators, low entry of new innovators and large size of innovators.

Indeed, coherent relationships exist between these indicators. First, correlation analysis for the various technological classes shows in all countries a positive correlation between concentration (C4) and asymmetries (HERF), stability of innovators hierarchy (SPEATOT and SPEACORE) and (although to a lesser extent) the size of innovating firms (SIZE), and a negative correlation between these measures and entry of new innovators (ENTRY).

Second, principal component analysis performed for all the technological classes identifies in all countries one dominant factor which captures a large fraction of the variance[4]. This factor discriminates in all countries between measures of concentration and asymmetries (C4 and HERF) and stability of the hierarchy of innovators (SPEATOT) on the one hand, and the variable ENTRY on the other. In other words, this component captures quite neatly the distinction between Schumpeter Mark I and Schumpeter Mark II technological classes.

Thus, one can conclude that the relationships between the various indicators of the patterns of innovation are actually related to the two Schumpeterian models and that the two alternative models discriminate significantly between technological classes.

What is even more important, moreover, is that the patterns of innovative activities are technology-specific, at least in the sense that strong similarities are observed in the pattern of innovative activities in the same technological class across countries:

a) The correlation coefficients for each indicator in the 49 technological classes across countries indicate that major similarities exist among countries in the sectoral patterns of innovative activities. That is to say, in the same technological class concentration, asymmetries, stability of the hierarchy of innovators and the role of new innovators tend to to have the same values across countries.

b) The characterization of a technological class as Schumpeter Mark I or Schumpeter Mark II is very similar across countries. If technological classes are grouped according to measures of Schumpeterian patterns of innovations, in all countries, most of them show similar patterns. Principal component analysis shows that many of the classes which were included in the Schumpeter I and Schumpeter II groups are quite similar in all countries. Specifically, 19 technological classes are consistently on the Schumpeter Mark I camp: clothing and shoes, furnitures, agriculture, chemical, analytical, physical processes, medical preparations, mining, chemical processes for food and tobacco, machine tools, industrial automation, industrial machinery and equipment, railways and ships, material handling apparatus, civil engineering and infrastructures, mechanical engineering, mechanical and electric technologies, household electric appliances, lighting systems, measurement and control instruments, sports and toys and the residual class "others". Conversely, 15 technological classes are consistently on the Schumpeter Mark II camp: gas, hydrocarbons and oil, organic chemicals, macromolecular compounds, biochemicals, bio- and genetic-engineering, aircraft, engines, turbines and pumps, laser technology, optics and photography, computers, other office equipment,

[4] 49% for Japan, 58% for the United States, 68% for Germany, 69% for France, 75% for the United Kingdom, 68% for Italy and 72% for the four European countries considered together.

electronic components, telecommunications, multimedial systems, ammunitions and weapons and nuclear technology.

In sum, Schumpeter Mark I technological classes are to be found especially in the "traditional" sectors, in the mechanical technologies, in instruments as well as in the white electric industry. Conversely, most of the chemical and electronic technologies are characterized by the Schumpeter Mark II model.

It has to be emphasized that important differences in the patterns of innovation across countries persist as a consequence of country-specific effects related to the national systems of innovation and the specific histories of firms and industries. These differences concern some general features of the patterns of innovation across all technological classes in each country, the values of some indicators in specific technological classes, the relationships between the variables which define the Schumpeterian patterns of innovation and the patterns of innovation in particular technological classes.

These differences emerge especially at the aggregate level, where one is able to identify "Schumpeter Mark II" countries (Germany, Japan, and to a lesser extent the USA), as opposed to Italy, typically a "Schumpeter Mark I" country. For example, if one compares the USA, Japan and the four European countries considered together, Japan emerges as a rather concentrated and stable country as opposed to Europe. The United States and Europe show similar features, although Europe is on average less concentrated and stable than the United States. If the comparison is made considering the individual European countries, Germany emerges as a typical "Schumpeter Mark II country": high asymmetries, concentration and stability, limited role of new innovators and high relevance of large firms. Conversely, Italy exhibits a "Schumpeter Mark I" pattern, despite a very high concentration. Japan looks quite similar to Germany, although it has a very high value of innovative entry. The other countries fall in between these extremes. The USA are characterized by low degrees of concentration (C4) and asymmetry (HERF), low innovative entry, high degrees of stability of the ranking of innovators within the core of companies which innovate continuously over time (SPEACORE): that is to say, innovative activities are widely diffused in a relatively stable group of innovators. The UK and France are quite similar, but the former country is characterized by a low stability of the ranking of innovators.

Differences can also be observed in the relationships between the various indicators in any individual country[5]. In particular, one can observe a major difference between Europe on the one hand and the USA

[5] In particular, in the USA there is no correlation, and in Japan a negative one, between the variable SPEATOT and the measures of concentration (C4 and HERF). Moreover, differently from the other countries, Japan is characterized by a low negative correlation between innovative entry (ENTRY) and concentration (C4) and asymmetries (HERF).

and Japan on the other in the relationship between concentration and stability. Similarly, the variables measuring respectively the stability in the ranking of continuous innovators (SPEACORE) and the size of innovating firms (SIZE) behave somewhat differently across countries. Finally, in Japan one observes differences from the other countries relatively more frequently as compared to other nations. However, on the whole these data and these indicators do not suffice in identifying clear and systematic national specificities.

Technological entry and exit

These results are confirmed by a more detailed analysis of the sectoral patterns of technological entry and exit (Malerba and Orsenigo, 1995a).

In general, technological activities (as measured by patents) are characterized by high degrees of turbulence. The population of innovators changes substantially over time, through birth and death processes. Entrants are slightly smaller firms than incumbents in economic terms, whilst exiters are sometimes bigger. Both entrants and exiters, however, are relatively small innovators in terms of the share of patent they hold.

However, one has to consider that entrants in any one technological class may well have innovated before in a different technological class. Similarly exiters may well start (or continue) to innovate in a different technology. Thus, gross entry (exit) has to be decomposed in two components: "net" entry and exit and "lateral" entry and exit.

In other words, turbulence in innovative activities is generated by four types of actors: net entrants, lateral entrants, net exiters and lateral exiters. The patterns of both net and lateral entry and exit are very similar to each other. Conversely, net entry and exit are quite distinct from lateral entry/exit. Net entrants and exiters are usually firms of small economic size with few patents each. Net entrants generate more patents than are lost by the net exiters. Lateral entrants and exiters are usually firms of large economic size engaged in a process of technological diversification, expanding the range of technologies in which they are active and eventually abandoning old technologies.

In assessing the performance implications of the entry of new innovators, it is important to know whether new innovators are occasional or persistent innovators.This means to explore whether and for how long they continue to patent after entry and whether they tend to increase or decrease their technological performance over time.

Data show that a large fraction of the new innovators ceases to innovate soon after entry and that survival decreases in the latest entry cohorts. As a result of the processes of entry and exit, the age distribution of innovators is strongly skewed towards the youngest and the oldest cohorts. On average, in the period 1989 -91 the 1978 -82 cohort was responsible for 16.6% of total innovators, the 1983-85 accounted for 11.3 %, the 1986-88 cohort for 13.7% and the 1989-91 for 58.3% of total innovators.

Data concerning the patent shares of firms that survived after entry confirm these results. The patent share of each entry cohort declines over time in each period and in each country. Moreover, each group of entrants is responsible for its largest share of patents in the period in which it is first observed and the patent share of each cohort of entrants in the first period after entry declines over time (from an average of 49.7% for the 1983-83 cohort to 40.6% for the 1986-88 cohort to 34.2% for the 1988-91 cohort), as the total population of firms increases. However, the patent share of the 1978-82 cohort (that is to say, the firms who were already present in the first period) remains the largest one in each subsequent period. Thus, the age distribution of patent shares in each period is highly skewed, with the oldest and youngest cohorts holding a far larger share of patents than the intermediate classes[(6)].

The decline in market share of each cohort as the cohort ages is the result of two conflicting forces: the change in the size (in terms of patents) of surviving members of the cohort and the exit of firms from the cohort. The "older" firms are indeed larger in terms of patents than the younger ones. Thus, in the period 1989-91 the average size in terms of patents of the firms in the 1978-82 cohort was 2.30 with respect to all innovators, against 1.15 for the 1983-83 cohort, 0.90 for the 1986-88 cohort and 0.58 for the 1989-91 cohort.

These results suggest that a large fraction of new innovators is composed by occasional innovators. They represent a large fraction of the whole population of innovators, but not necessarily of the total number of patents at any given time.

However, another fraction of entrants survives and grows larger in terms of patents as times goes by. These older firms who survive and continue to patent represent an important contribution to total patenting activities in any period. This is a clear indication of the presence of cumulativeness in technological knowledge and the process of building up of technological capabilities and competitive advantages by those firms that are able to survive. These capabilities and advantages generate a continuous stream of innovation by surviving firms.

What is more important, also the patterns of natality and mortality show substantial diversity across technological classes. First, the entry

[(6)] On average, in the period 1989-91, the 1978-82 cohort was responsible for 35.9% of total patents in that period, the 1983-85 and 1986-88 cohorts has both 14.4% and the youngest cohort (1989-91) had 34.2 %.

variables and the exit variables are systematically related to each others within any one technological class. In particular, all the indicators measuring the importance of innovative natality are positively correlated to each other and to the corresponding indicators of mortality. In other words, natality and mortality occur simultaneously in each technological class.

Second, gross entry and exit are negatively correlated with lateral entry and exit. That is to say, technological classes characterized by high turbulence show simultaneously and consistently a lower relative role of lateral entry and exit.

In sum, two different types of technological classes emerge:

a) One group is composed by turbulent classes: high gross entry and exit with most of the entry generated by totally new innovators and most of the exit by firms which stop patenting.

b) A second group is composed by stable classes: low gross entry and exit, largely associated to processes of technological diversification of firms. In these technological classes, lateral entrants tend to be relatively big (and net entrants small). Conversely exiters (especially net exiters) tend to be smaller innovators.

Finally, in most countries turbulent and stable technological classes tend to be the same: 21 technological classes are consistently stable and 12 classes tend to be consistently turbulent. 16 remaining classes show more variation across countries or do not fit neatly into these two categories. The stable group comprises most of the chemical and electronic technologies, vehicles and aircraft; the turbulent group includes mechanical technologies, traditional technologies (e.g.furniture) and agriculture.

Again, it is possible to claim that the sectoral patterns of innovative entry and exit are remarkably similar across countries.

PATTERNS OF INDUSTRIAL DYNAMICS

Together with the patterns of innovation, a growing body of empirical studies highlights some important stylized facts about industrial dynamics.

Entry, exit, market "turbulence"

A first set of "stylised facts" concerns the rates of entry and exit. It appears that most industries are characterised by significant degrees of turbulence (Acs and Audretsch, 1990, Beesley and Hamilton, 1984).

That is to say, the firms composing a given industry are constantly changing, through processes of entry and exit.

In particular, gross entry is a pervasive phenomenon in manufacturing (and more so, in service industries). Birth rates are quite high in most industries, even in those characterised by high degrees of capital intensity (Acs and Audretsch, 1989 and 1991).

Most entrants are small firms, far below any measure of efficient minimum scale, and a large percentage of new entrants exits the industry within few years after entry. However, an important source of entry is stemming from incumbent firms operating in other industries or countries which diversify into other sectors. In this case, entry often occurs via acquisition of existing plants. The role of this second type of entry is limited in terms of number of firms, but much more important in terms of share of output or employment.

It must be noticed also that we know very little about the degree of turbulence in the "core" of the industry, among large firms. Older studies (Kaplan, 1964, Collins and Preston, 1961, Mermelstein, 1969, Bond, 1975) suggested a relative stability in the hierarchy of large firms: rates of turnover among the largest corporations appeared to be small and declining over time. Acs and Audretsch (1991) confirm that turbulence among small firms is higher than among large firms by an estimate of 35% in the 247 manufacturing industries included in their sample.

Mortality is however high too, so that net entry is much smaller than gross entry and significant turbulence characterises industrial evolution. Moreover, the probability of survival increases or at least variation in performance stabilises with size and age (Aldrich and Auster, 1987, Acs and Audretsch, 1991 and 1992).

These results would seem to suggest that turbulence is primarily a characteristic of the fringe of the industry. This is confirmed by the observation that substitution of "old" firms with "new" firms occurs to a much larger extent among small, young firms which are relatively similar to each other. In other words, entrants in the fringe often are not more efficient than the incumbents. Turbulence is instead lower in the core of the industry and among larger firms.

Turbulence differs drastically across sectors, however. Econometric literature investigating the determinants of birth rates is now burgeoning and it is now possible to draw some consistent results.

i) Turbulence tends to be comparatively lower in industries characterized by high rates of innovation and advertising, high capital intensity, low concentration, low growth (Acs and Audretsch, 1991).

However, one has to distinguish between the determinants of gross entry, net entry and exit and between large and small firms.

ii) In particular, advertising appears to constitute a greater barrier than capital intensity to both gross and net entry, irrespectively of firm size. Concentration seems to inhibit entry of small firms but not of large companies. Similarly, high rates of innovation do not necessarily deter small firms from entry. In certain industries, in which small firms account for a significant share of total innovative activities, birth rates are rather high.

Evidence is less clear about the role played by variables like industry growth and profitability. The latter variable does not seem to have any significant effect in attracting entry, whilst mixed results are obtained for industry growth. Similarly, the growth of GNP (but also unemployment) appear to trigger new firms formation. In any case, there appears to be no robust evidence about the cyclical behaviour of birth and death rates. Some studies report strong correlation between indicators of favourable macroeconomic conditions, birth rates (positive) and death rates (negative). Other studies however find absence of correlation or even inverse correlation (as in the models of self-employment).

iii) The probability of exiting the industry increases for small and young companies (Acs and Audretsch, 1990, Evans 1987a and 1987b, Dunne, Roberts and Samuelson 1988 and 1989, Aldrich and Auster, 1987)[7]. Moreover, the probability of survival of new, small firms appear to be lower in capital-intensive industries, and in sectors characterized by high rates of innovation and high economies of scale. However, further distinctions need to be made. Concentration, scale economies and capital intensity actually seem to facilitate survival in the short run, but not in the long run. Indicators of innovativeness do not affect survival in the short run, but only in the long run. Moreover, survival is also easier in those industries in which small firms are important sources of innovation.

Finally, it must be noted that surviving firms have either a higher initial size or higher growth rates. Bigger initial size implies lower growth, but higher survival. Surviving new firms tend to grow faster in innovative industries. Scale economies and capital intensity have a positive effect on growth in the short run: surviving firms tend to grow faster in the early periods, but afterwards those disavdantages do not matter.

In sum, capital-intensity does not affect entry but survival and thus turbulence. Surviving firms appear to grow faster as a function of the gap between minimum efficient scale (MES) of output and firm size. At the same time, however, the likelihood of survival decreases as a function of that gap. The same happens in terms of innovation rates. Thus, fac-

[7] The literature on population ecology provides further important empirical evidence on these points. See Hannan and Freeman (1990) among others.

tors promoting growth reduce survival and vice-versa. An exception is the industry growth rate, which has a positive effect on both growth and survival.

Inter-firm asymmetries

A second set of stylised facts concerns the existence and persistence of significant differentials in productivity (Nelson and Winter, 1982) and profitability across firms and (at least in the US) across industries (Mueller, 1990). Firms enjoying higher (lower) profits tend to earn higher (lower) profits in the future. That is to say, profits do not converge on a common rate of return, but some firms earn above normal rates of return for a statistically unspecified "long time".

The observed persistence of profitability differentials reflects both the existence of permanent differentials in "efficiency" among firms, which are not eroded away by the competitive process and the sluggishness of the competitive process that should generate convergence to "long run equilibrium". However, the evidence seems to indicate that the adjustment of profits to "permanent" values is relatively quick, although high variability is observed in across country comparisons (Geroski, 1988, Geroski and Masson, 1987).

Persistence of profits appears to depend both on industry-specific characteristics and on firm-specific characteristics. In particular, industry-specific features as the intensity of advertising and R&D appear to be robust explanatory variables of the persistence of profits above the norm. The significance of firm-specific variables, on the other hand, varies across sectors. Firm-effects are important within any one industry. Thus, for instance, market share is positively related to profitability in the presence of high advertising and patent intensity.

Empirical evidence is rather fuzzy as it concerns the effects of industry and firm-specific variables of the speed of adjustment. Important differences among countries and industries emerge in both the extent to which profit differentials permanently persist and in the speed of adjustment to "equilibrium". In general, however, firm-specific variables are more important in explaining the long-run "equilibrium" levels of company profits, whilst industry-specific variables are more important in the explanation of the adjustment process to those long-run equilibrium values. In the USA, excess returns appear to erode more slowly in highly concentrated industries, experiencing rapid demand growth, and characterized by significant economies of scale, large absolute capital requirements, large sunk outlays and high advertising expenditures (Kessides, 1990). (Other studies, however challenge these results, cf. Odagiri and Yamawaki, 1990).

Size distributions

The last set of stylised facts concerns the remarkable stability of a skewed distribution of firm and plant size, approximately a Pareto distribution, with the highest frequency found with small companies. This phenomenon has been conventionally accounted for by some version of Gibrat's Law of proportionate growth, i.e. independence of growth rates from size. However, empirical evidence in this respect is rather inconclusive, the results depending on the particular specification and on the sample used. Considering only the more recent studies, Hall (1987) and Evans (1987 a, 1987b) found that both the firm growth rates and their variation decrease with size (and age, in Evans studies). Conversely, Acs and Audretsch (1991) find confirmation for Gibrat's Law, by including in the sample firms exiting the industry. Indeed, as it have been documented by several studies (Aldrich, Evans, 1987a and 1987b, Hall, 1987) small (and young) firms tend to exit with greater frequency than large companies. Thus, consideration of exit offsets to some extent the higher growth rates of small firms.

Results are even fuzzier at the industry level. Acs and Audretsch (1990) for instance, found that growth rates are significantly different across firm-size classes in about 40% of the industries considered in their sample. Sectors in which Gibrat's law is not confirmed include petroleum, rubber and plastics, paper, leather. Conversely, Gibrat' law appears to hold in furniture, printing, chemicals, fabricated metals, transportation equipment and instruments.

"Life-cycle" patterns

The properties of industrial structures and dynamics discussed so for pertain to broad aggregates, such as "manufacturing", or "industries" – the way they are defined by conventional statistics, say, at 2- or 3- digit levels. However, the locus of innovation, competition, entry and exit is to be found at a much more disaggregate level of observation: it is not e.g. "chemical" or even "pharmaceuticals" but, say, "antibiotics", "ß-blockers" or, within other industrial codes, "integrated circuits", "laser-printer", etc. Within micro sectors, one has identified some typical patterns of evolution along what is sometimes called the "life cycle" of a particular technology or group of products[8]. These patterns (not entirely uncontroversial) are summarized by Klepper (1992) as follows:

[8] On various features of the dynamics of entry, exit, innovation within 'life cycles' see Klepper (1992). Overlapping or complementary evidence stems from the growing field of "organizational ecology": see Hannan and Freeman (1990).

"1) There is an initial period of fairly steady growth in the number of producers followed by a period in which the number of producers declines sharply;

2) the time path in the number of entrants up to the peak number of producers does not follow a common pattern for all new products, with the number of entrants sometimes rising up to the peak whereas in other instances it reaches a maximum well before the peak. For all products, though, entry tends to peak at or before the peak in the number of producers and then falls off sharply and stays below exit throughout the shake-out;

3) the number of major product innovations tends to reach a peak during the period of growth in the number of producers and then falls over time;

4) during the period of growth in the number of producers, the most recent entrants account for a disproportionate share of product innovations;

5) over time, increasing effort by producers is devoted to process relative to product innovation;

6) over time, the rate of change of firm market shares slows.". (p. 7).

TECHNOLOGICAL REGIMES AND PATTERNS OF INNOVATIVE ACTIVITIES

Technological regimes as determinants of the patterns of innovative activities

The evidence reviewed so far on the patterns of innovative activities and on industrial dynamics provides an extensive array of problems to explain. As such, each of the stylized facts mentioned previously constitutes somewhat of a puzzle. The more so, if these facts are considered simultaneously. For instance, the evidence on the sectoral specificities in the patterns of innovation and turbulence and on the persistence of differential innovative performance and profitability over time clearly contrasts with an explanation of the stability of firm size distribution based on some version of Gibrat's Law, whereby independence of the variance of growth from initial size is assumed. Similarly this last assumption is clearly at odds with the reported evidence on the relationship between size and age on the one hand, growth and survival on the other.

In general, evidence seems to suggest the existence of:

a) strong firm and sector specificities in the patterns of innovation and industrial dynamics. In particular, as it concerns innovative activities, one can meaningfully identify two groups of technological classes: "Schumpeter Mark I" and "Schumpeter Mark II" classes; b) rather permanent factors at the firm level which generate persistence of innovative and economic performance over time and c) discontinuities and shocks which may change radically from time to time the competitive advantages/disadvantages of individual firms and the patterns of industrial dynamics.

Empirical research provides also some indication towards a preliminary interpretation of these phenomena. In particular, the economics of innovation suggests a few useful concepts in this respect.

First, innovation studies have started to disentangle the plausible idea that innovative activities are to be analyzed as a complex learning process. Such processes are inherently cumulative and generate specific competences which define what a firm can do (and what it cannot do) and where a firm can search when trying to improve its technological and economic performance. In this perspective, firms are defined by their competences. Their ability to change is heavily constrained by the level and nature of their competences (Teece and Pisano, 1994; Dosi and Marengo, 1993). On these grounds, one would expect to observe high degrees of diversity and variety in firms competences, as well as relatively high degrees of persistence in their activities and performance. That is to say, firms appear to be able to build up over time specific capabilities and assets which shelter them from selection and make them persistently "better" (or worse) than competitors.

Second, and relatedly, it has been suggested that technologies differ drastically and that their development retains a strong autonomous internal logic. The notion of technological paradigms and trajectories tries to capture this insight (Dosi, 1982; 1988). It must be noted that paradigm shifts imply radical changes in the relevant competences, in the directions and procedures of technological change and — as a consequence — also significant changes in the relative innovative capabilities and "efficiency" of firms.

Third, in a related way, the results discussed previously suggest that "technological imperatives" and technology-related factors play a major role in determining the specific pattern of innovative activities of a technological class across countries. Specifically, we propose that the observed sectoral patterns of innovative activities are related to the nature of the relevant technological regime.

The notion of technological regime dates back to Nelson and Winter (1982) and provides a description of the technological environment in which firms operate. More generally, Malerba and Orsenigo (1990 and 1993) have proposed that a technological regime is a particular combination of some fundamental properties of technologies: opportunity and appropriability conditions; degrees of cumulativeness of technological knowledge; characteristics of the relevant knowledge base.

Opportunity conditions reflect the easiness of innovating for any given amount of money invested in search. High opportunities represent a powerful incentive to the undertaking of innovative activities[(9)]. In addition, opportunity conditions may be highly pervasive or not. Highly pervasive opportunities may mean that the generation of new knowledge may be applied to a variety of products and markets. On the contrary, low pervasiveness means that the generation of new knowledge concerns only a limited and specific set of products and processes.

Appropriability conditions summarise the possibilities of protecting innovations from imitation and of extracting profits from innovative activities[(10)].

Cumulativeness captures the properties that today innovations and innovative activities form the starting point for tomorrow innovations and that today innovative firms are more likely to innovate in the future in specific technologies and along specific trajectories than non innovative firms.

Technologies differ also in terms of the characteristics of their knowledge base. The knowledge base can be primarily tacit, local and firm-specific or rather codified and "universal" and thus relatively more easy to get access to. Similarly, the relevant knowledge base may show varying degrees of complexity because innovations may require he integration of different scientific disciplines and technologies, and because innovative activities may be fed by the contribution of a variety of competences concerning the production process, the nature of markets, the features of demand and so on. Some of these competences may be external to the firms in the industry and may derive from e.g. suppliers of materials, equipment producers, users, universities and government laboratories.

The notion of technological regime has indeed proved to be useful in providing a framework for interpreting a substantial body of empirical evidence on firms organization and strategies and on the sectoral patterns of technical change and industrial dynamics. Moreover, some direct evidence of the role of variables which constitute a technological regime and the patterns of innovation is now becoming available.

What follows summarizes the links between technological regimes and the patterns of innovative activities both at the conceptual and the empirical level.

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(9) Science is certainly a major source of opportunities. Yet, the sources of opportunities differ among industries and technologies. As Rosenberg (1982) and Nelson (1992) have shown, in some industries opportunity conditions are related to advancements in science; in others, research equipment and instrumentation or external sources of knowledge, such as suppliers and users, play a major role.

(10) As known, firms utilize a variety of means in order to protect innovations, ranging from patents, to secrecy, to continuous innovation, to the control of complementary assets (Levin *et al.*, 1987; Teece, 1986).

Technological regimes, firms' strategies and organization

Notice first that the notion of technological regimes can provide the basis of an explanation of some aspects of the dynamics of firms organization and strategies. The nature of the specific technological regime in fact identifies some problem-solving tasks which are common to all the firms active in a particular industry.

For instance, Dosi, Teece and Winter (1992) use some features of learning activities to explain the coherence and the patterns of diversification of business firms. In a similar vein, Malerba and Orsenigo (1993) provide a discussion and some evidence based on case-studies on the relationships between firms innovative strategies (defined very roughly as radical, incremental and imitative) and technological regimes.

Notice, first, that high opportunity conditions tend to make relatively more attractive the pursuit of strategies of radical search and exploration of new innovative opportunities (March, 1991). Moreover, insofar as technological progress is rapid and innovations are generated from every quarter, high opportunities imply also that companies have to establish windows and channels of communication with the external environment (e.g. scientific institutions) in order to keep pace with progress. In terms of organisational structures, this entails that a company must be prepared to jump rapidly and continuously on the new opportunities, changing and adapting quickly its research organisation. High cumulativeness conversely implies a strategic bias in favour of incremental search and of the exploitation of existing technologies and capabilities. Moreover, it implies a tendency towards an increasing specialisation of innovative activities along specific directions.

Low appropriability conditions imply that imitative strategies are viable for followers and that innovative firms have to view the protection of innovations as a key strategic dimension in their innovative activity, possibly also via the development of complementary assets (Teece, 1986).

The combination of these conditions identifies therefore some general strategic trade-offs which firms have to cope with and sets of "viable strategies". In different technological regimes firms face different strategic imperatives and options. Let us consider some examples.

Think of a combination of high opportunity and high cumulativeness: this determines a major tradeoff between the continuous exploitation of existing technologies and the continuous exploration of new technologies. Sole exploration may imply too high costs of finding radical innovations without being able later on to fully profit from them. Sole exploitation may imply the risk that firms may end up being locked-in in existing technologies, without moving rapidly and forcefully to the new ones.

In the case of high opportunity and high appropriability, but low cumulativeness, firms may be induced to follow mainly strategies of exploration of new technologies. For example, this is the case of biotechnology, where established firms have to monitor what is going on the technological frontier and develop extensive network of collaboration between new specialized biotechnology companies, pharmaceutical firms and universities. On the contrary, in case of high cumulativeness and high appropriability, but low opportunity, strategies of exploitation of existing technologies are the only viable strategies. This is the case of firms involved in the production of very large scale integration semiconductor memories.

However, in conditions of high opportunity, high cumulativeness and high appropriability, firms may follow either strategies of exploration of new technologies, or exploit existing technologies or some combination between the two like strategies of exploration of new technologies followed by exploitation of these technologies. Semiconductor firms' strategies based on a combination between the introduction of major innovations, rapid movements down the learning curve in existing products and on the continuous improvement of established components within a broad product family are a case in point.

In general, high opportunity, high cumulativeness and low appropriability imply more complex strategic tasks, but also higher degrees of strategic freedom, i. e. the number of viable strategies is likely to be bigger. High opportunity allows "exploration strategies", high cumulativeness allows "exploitation strategies", while low appropriability allows also follower firms to pursue imitation strategies. Conversely, when regimes are characterized by low opportunity, the menu of viable strategies becomes narrower.

Two further dimensions which affect the set of viable strategies relate to the pervasiveness of opportunities and the complexity of knowledge. Pervasiveness implies opportunities for diversification through the application of the core technological knowledge to a variety of products and markets. Conversely, lack of pervasiveness (i.e. specific opportunities), particularly if coupled with high degrees of cumulativeness, entails a tendency towards product and market specialization. Thus, diversified companies will tend to emerge in regimes characterized by pervasive opportunities and low cumulativeness, whilst specialist companies are more likely to emerge in highly cumulative and non pervasive technologies.

The properties of the knowledge base identify some further tradeoffs and imperatives. The more the knowledge base is tacit, the stronger is the need to develop internal codes and channels of communication, and the weaker is the ability and the possibility to transfer it to other firms and institutions. The more the knowledge base is complex, the stronger is the need for firms to develop mechanisms for the integration of its various components.

If appropriability is high and knowledge is codifiable, complexity may allow firms to specialize in specific innovative activities generating only part of the relevant know-how. These specialized companies may coexist and establish complementary relationships with "system integrators" which then may make use and put together knowledge produced externally. This is the case of the software industry, rich with specialist firms and system integrators.

On the contrary, low appropriability conditions and high degrees of tacitness of the knowledge base favour strategies and organizational solutions directed towards full integration through the control and the integration of various innovative activities, and the development of complementary assets and of strong internal codes of communication (von Hippel, 1988; Teece, 1986; Mowery, 1983).

In case of high appropriability and tacitness of the knowledge base, firms may be induced to develop strategic alliances. This is because knowledge cannot be easily exchanged nor replicated: hence, the incentive for firms to join in long term agreements concerning common innovative activities.

In general, high complexity of the knowledge base and high opportunity conditions make it more likely that firms develop external networks. Even a company like IBM, for a long time fully vertically integrated, had since the early 1980s to form cooperative agreements and strategic alliances with software firms, users and component producers.

Finally, in case of high pervasiveness and high complexity, a major organizational trade-off concerning centralization and decentralization may emerge, particularly when knowledge is tacit. Without entering into this issue in any detail, let us just mention that the need to develop full integration through a centralized organizational structure in order to coordinate and exploit at a complex core capabilities may clash with the need to decentralize the organisational structure for the exploitation of the opportunities for diversification. (Pavitt, 1990; Marengo, 1991).

Technological regimes and the sectoral patterns of innovative activities: indirect evidence

The notion of technological regime provides also the basis of an explanation of the variety in the patterns of innovation across sectors (and/or technologies).

The introduction even of rough proxies of opportunity and appropriability conditions significantly improves the performance of econometric tests on the relationships between market structure (e.g. firm size and degrees of concentration) and innovation (Cohen and Levin, 1989).

Malerba and Orsenigo (1990) discussed the main relationships between the variables which define a technological regime and the various measures of the sectoral patterns of innovation and showed in the case of Italy that the nature of technological regimes highly affects the specific patterns of innovative activities at the sectoral level. In particular, a high concentration of innovative activities is related to high opportunity, appropriability and cumulativeness conditions, while high stability in the hierarchy of leading innovators is related to high appropriability and cumulativeness conditions. Finally, the ease of entry of new innovators in an industry is related to high opportunity and low cumulativeness conditions. Thus, "Schumpeter Mark I" sectors are characterized by high opportunity and low appropriability conditions, which favor the continuous entry of new innovators in the industry, and by low cumulativeness conditions, which do not allow the persistence of monopolistic advantages in the industry by any one innovator. "Schumpeter Mark II" patterns are determined by high opportunity, high appropriability and high cumulativeness conditions, which allow innovators to incrementally accumulate technological knowledge and capabilities and to build up innovative advantages over non-innovators and potential entrants.

The remarkable similarity in the sectoral patterns of innovative activities across countries provides some further indirect evidence of the relevance of technological regimes in determining some sectoral invariances in the patterns of technological change (Malerba and Orsenigo, 1993).

Note that the patterns of innovations ought to be rather invariant across countries, as long as opportunity, appropriability and cumulativeness conditions -i.e. the dimensions of technological regimes that affect the widening and deepening patterns of innovation – are similar across countries. There is indeed some evidence that appropriability and cumulativeness conditions are rather similar across advanced industrialized countries (see Malerba and Orsenigo, 1990 and Heimler, Malerba and Peretto, 1993 for an analysis of the Italian and American cases) across a wide range of technologies. The ability to generate and exploit opportunity conditions is however less similar among advanced countries, because this ability is related to the level and range of university research, the presence and effectiveness of science-industry bridging mechanisms, vertical and horizontal links among local firms, user-producer interaction and the types and level of firms' innovative efforts (Nelson, 1992).

Technological regimes and the sectoral patterns of innovative activities: direct evidence

Some direct evidence on the relevance of technological regimes in explaining the patterns of innovation across sectors is also becoming available.

Cumulativeness, persistence and the patterns of innovation

A first set of results concerns the role of cumulativeness. Actually, the notion of cumulativeness may have different meanings and interpretations and can be measured in different ways.

To clarify the issue, consider, for a moment, innovation as a purely random shock in a firm's technological domain. In the simplest statistical interpretation, then, the notion of cumulativeness may be more generally interpreted as persistence in innovative activities and can be defined as the differential probability that innovators at time t will innovate at time $t + 1$. More precisely, one can think of persistence as the degree of serial correlation in innovative activities and consider innovation as a purely random process that the firm does not control.

Innovation, however, results from the actions of economic agents and it is fundamentally affected by opportunities and constraints that are defined by the characteristics of technologies and markets. Thus, persistence of innovative activities is likely to be generated by some properties of the processes of accumulation of technological competences and by market processes.

In its simplest economic interpretation, the notion of innovative persistence can be related to the the Schumpeterian intuition that critical market feed-backs link R&D investment, technological performance and profitability (Schumpeter, 1942). For instance, persistence may be simply the outcome of "success-breeds-success" processes like those used in Nelson and Winter models: innovative success yields profits that can be reinvested in R&D, thereby increasing the probability to innovate again.

In its simplest technological interpretation, the notion of innovative persistence can be related to the notion of technological cumulativeness, i.e. technical change is gradual and incremental, since it builds on accumulated competencies in the firm's technological domain (Rosenberg, 1976). An innovation generates a stream of subsequent innovations, which improve gradually on the original one. Thus, persistence may be the outcome of the intrinsically cumulative nature of learning processes (Rosenberg, 1976; Nelson and Winter, 1982). The generation of new knowledge builds upon what has been learned in the past not only in the sense that past knowledge constrains current research, but also in the sense that knowledge generates questions and in turn new research. Moreover, research is usually characterized by dynamic increasing returns (in the form of e.g. learning-by-doing, learning-to-learn, etc.), and today's research generates tomorrow's new opportunities (Klevorick *et al.*,1993; Cohen and Levinthal, 1989).

Innovative persistence may derive also from organizational features at the firm level. For instance, persistence might be generated by the establishment of R&D facilities at a fixed cost, which then produce a relatively stable flow of innovations. More generally, however, persistence is likely to be originated by firm-specific technological and organizational capabilities, which can be improved only gradually over time and thus define what a firm can do now and what it can hope to achieve in the future. In this respect, persistence of innovative activities is likely to be strongly related to heterogeneity in the population of innovators. Heterogeneous agents, characterized by different competences in different technological domains show different innovative capabilities that are likely to persist over time. Persistence will then reproduce such differences, generating further heterogeneity.

Serial correlation, technological cumulativeness and economic feed-backs constitute different aspects of the same phenomenon. Technological cumulativeness and market feed-backs relate respectively to the cognitive and to the strictly economic aspects of the innovative process. Serial correlation, on the other hand captures the observable statistical properties of the process. In practice, it may be very difficult to distinguish the technology-specific, the firm-specific and the market-specific sources of serial correlation in innovative activities. To the extent that cumulativeness and market feed-backs are not observable, firm-level serial correlation can be considered as an indicator of the persistence of innovative activities generated by technology and market processes.

Various theoretical models have examined the effects of serial correlation in innovative activities upon the patterns of technical change and industrial dynamics. For instance, Winter (1984) showed via simulations that innovative persistence generates high rates of innovation, concentration and stability in the ranking of innovators and low innovative turnover as measured by the rates of entry of new innovators and exit of old innovators. Similar results are obtained by Dosi *et al.* (1995) and will further be discussed in some more detail.

Malerba, Orsenigo and Peretto (1995) calculated indicators of firm-level innovative persistence, using again the OTAF-SPRU database for five European countries (Germany, UK, France, Italy and Sweden). These indicators are obtained by exploiting the microeconomic information contained in the data. They estimated for each technological class in each country (165 regressions in all), the dynamic panel data model with variable intercept:

$$P_{it} = \alpha P_{it-1} + \beta_i + u_{it} \quad i = 1, ..., N \text{ and } t = 1, ..., T \tag{1}$$

where N is the number of firms in the panel for each technological class in each country and T is the number of years in the panel, 18; $|\alpha| < 1$ is a time invariant sectoral coefficient of firm-level autocorrelation in the patenting process and β_i is a time-invariant firm-specific random effect[11].

The instrumental variable estimator for the autocorrelation coefficient α is our indicator of persistence. Moreover, the variance of the firm-specific random effects (σ^2_β) provides an estimate of the heterogeneity in the population of innovators.

Malerba, Orsenigo and Peretto (1995) then examined the relationships between persistence, heterogeneity and the observed patterns of innovative activities across sectors and countries. The dependent variables are the index of technological concentration, HERF; the indexes of stability of the rank of innovators, SPEATOT for the whole sample and SPEACORE for the firms that innovated consistently over the entire period considered; an indicator of innovative intensity, i.e the sectoral intensity of innovative activities at the firm-level, (AVSTOCK, average number of patents per firm)[12].

The independent variables include, first, the indicators of persistence and heterogeneity and, second, measures of market structure, i.e. average firms' size in terms of employment (AVEMPL) and economic concentration in terms of employment (HERFEMPL). In addition, other control variables were included, namely, the relative rates of technological natality and mortality in terms of numbers of firms, NATFIRM and MORFIRM. The latter were considered as exogenous variable, although they might well be partly determined by the same factors which determine technological concentration and stability in the rank of innovators. However, technological entry and exit in terms of number of firms are likely to depend on many other factors (related to e.g. market structure), for which no measures were available, and to be generated by processes much more complicated than the one used by Malerba *et al.* (1995)[13]. Finally, dummy variables for sector and country-specific effects were introduced.

That is to say, the exercise tries to assess whether persistence, hetero-

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(11) The standard assumptions on the disturbances and the firm-specific random effects are made (see e.g., Hsiao, 1986, chap. 4). Namely, the disturbances u_{it} satisfy $Eu_{it} = 0$, and $Eu_{it}u_{js} = \sigma^2_u$, if $i = j$ and $t = s$, and $Eu_{it}u_{js} = 0$ otherwise. The random effects satisfy $Eb_i = 0$, $Eb_ib_j = \sigma^2_b$ if $i = j$ and $= 0$ otherwise.

(12) Please note that this variable is not really an indicator of the rates of innovation, but only of the intensity of patenting activities. This indicator is obviously influenced by the total number of patents, but also by the total number of firms within a technological class. Thus, similar values of AVSTOCK might reflect simply different structures of the patterns of innovation, e.g one characterized by a large number of patents and a large number of firms and the second vice-versa. In this acception, innovative intensity might be considered as a synthetic indicator of whether technological progress follows a "creative destruction" or a "creative accumulation" model.

(13) A final motivation for considering these two variables as exogenous relates to the problem of censoring. The inclusion of NATFIRM and MORFIRM among the set of the explanatory vaiables can imperfectly control for the effects of censoring on the estimates.

geneity and market structure bear any significant relationship with the variables defining the patterns of innovative activities. The analysis of the relationship between market structure and innovation was obviously the main concern of the debate on the so-called "Schumpeterian hypotheses" (Kamien and Schwartz, 1982; Cohen and Levin, 1989). Malerba *et al.* (1995) widen this strand of analysis in two ways: first, they fully recognize the importance of the insight that sector and technology-specific variables (i.e., technological regimes) may be very important factors in determining the intensity of innovative activities. Second, they use new indicators of the conditions of the technological regime, like the measures of persistence and heterogeneity, as well as rather unconventional indicators of market structure like the rates of innovative entry and exit.

Summarizing a lengthy discussion, the results of this analysis show that persistence and asymmetries are important (and strongly related) phenomena that affect the patterns of innovative activities across countries and sectors. In particular, concentration in innovative activities is associated positively with persistence and technological asymmetries on the one hand and with industrial concentration on the other; negatively with average firms' size (Adj R^2 = 0.637). Stability in the ranking of innovators is related only and negatively to the processes of technological entry and exit (NATFIRM and MORFIRM) (Adj R^2 = 0.852). Conversely, stability of the rank of innovators for the firms that innovated consistently over the entire period considered (SPEACORE) is positively associated to both persistence and technological asymmetries, but not to the processes of entry and exit (Adj R^2 = 0.219). Finally, innovative intensity is positively associated to persistence and to technological asymmetries and negatively to technological entry and exit (Adj R^2 = 0.919).

In other words, innovative persistence and technological asymmetries tend to generate high degree of innovative concentration, high stability in the ranking of innovators and high innovative intensity. Moreover, the dependent variables (i.e. the variables measuring the patterns of innovative activities, except innovative concentration) are negatively influenced by high rates of innovative entry and exit. Entrants and exiters are typically small and occasional innovators who operate in the fringe of the industry. Thus, turnover affects the stability in the ranking of innovators but it does not affect innovative concentration. In sum, these results confirm that persistence and technological asymmetries are associated to a typical Schumpeter Mark II model[(14)].

[(14)] Regressions were also run for the dependent variables entry and exit of innovative firms measured in terms of their share of patents (NATPAT, MORPAT). In these cases, the specification clearly omittted the variables NATFIRM and MORFIRM. Thus, these two regressions cannot be directly compared to the previous set of exercises. In any case, both the dependent variables are negatively associated to persistence and technological asymmetries. Moreover, average firms' size affects negatively the exit variable but not the entry variable. These results therefore would seem to provide further corroboration to the hypothesis that persistence and asymmetries tend to generate Schumpeter Mark II type patterns of innovative activities.

Market structure variables (especially firms size) do not seem to play instead any overwhelming influence on the patterns of innovation, the only significant relationship observed being between market concentration and innovative concentration.

Technological opportunities, appropriability and the sectoral patterns of innovation

A second attempt at trying to assess directly the relationships between the variables which define technological regimes on the one hand and the Schumpeterian patterns of innovation on the other has been provided by Breschi, Malerba and Orsenigo (1966).

Two major sources of data have been used in the paper. First, European Patent Office (EPO) data on patents applications by firms of three countries (Italy, Germany and United Kingdom) for the period 1978-91 have been used to construct the various measures of the sectoral patterns of innovative activities. Five measures of patterns of innovative activities are considered in the paper. In addition to the indicators discussed previously of innovative concentration (the Herfindahl index, HERF, and the concentration ratio, C4) and of the degree of dynamism and turbulence present in each technological class (technological entry, ENTRY and the degree of stability of the hierarchy of innovators, SPEATOT), an additional measure has been constructed. In order to group technological classes according to measures of Schumpeterian patterns of innovative activities, principal component analysis has been performed for all the 49 technological classes (see Malerba and Orsenigo, 1996). The individual scores resulting from such analysis have been used to construct a synthetic measure of the sectoral patterns of innovative activities (PRINCOMP).

Second, data on industry-specific technological conditions (i.e. technological regimes) were drawn from the recent PACE (policy appropriability and competitiveness for European enterprises) questionnaire survey coordinated by Merit Institute (The Netherlands). The survey was addressed to 713 R&D executives from the European Union's largest manufacturing firms with the aim of obtaining their opinions on a broad range of innovation-related issues: goals of innovation, external sources of knowledge, public research, methods to protect innovations, government programmes to support innovation, and barriers to profiting from innovation. The unit of analysis was the line of business, as defined by four-digit ISIC (1989, third revision) sectors, of the R&D manager who received the questionnaire. On the whole, the 713 sample business units were operated by 414 firms in 101 manufacturing sectors.

This latter dataset has been used to compute indicators of the variables which define a technological regime. The relevance attributed to science as a source of innovation across industries has been used to capture the level of technological opportunities. Survey respondents were asked to rate (on a five-point Likert scale) the importance to the progress of their unit's technological base of ten fields of basic and applied science over the past ten years. The variable BASSCIENCE represents for each individual respondent the sum of scores received by the fields of basic science: biology, materials science, chemistry, medical and health, physics, chemical engineering, mathematics. The variable APPSCIENCE represents instead the sum of scores received by the fields of applied science: electrical engineering, computing science and mechanical engineering.

Appropriability conditions are measured with responses (on a five-point Likert scale) to questions concerning the effectiveness of two methods used by firms to prevent competitors from copying product and process innovations: patents and secrecy. The variable APPROPRIABILITY is for each individual respondent the sum of scores received by each of these two mechanisms for either process or product innovations.

In order to measure cumulativeness conditions, Breschi *et al.* (1995) resorted to a question related to the frequency of product innovations. Survey respondents were asked to evaluate (on a five-point Likert scale) the importance of frequent technological improvements in making their unit's product innovations difficult or commercially unprofitable to imitate. The score received by this question – CUMULAT – can therefore be assumed as a proxy of the degree to which technical advances in a given industry take place in a "cumulative" way.

Using the various measures of Schumpeterian patterns of innovation as dependent variables, the role played by technological regimes has been tested by performing regression analysis (OLS). The main results which emerge from such analysis can be summarized as follows. In the first place, all industry characteristics (i.e. technological regimes) are individually significant at the conventional statistical level and have the expected sign. In particular, APPROPRIABILITY, CUMULAT, and BASSCIENCE are significantly and positively related to concentratio ratio of innovators (C4), asymmetries among innovators (HERF) and stability in the hierarchy of innovators (SPEATOT), as well as to PRINCOMP, while they are negatively related to entry of innovative firms (ENTRY). However, an interesting and to some extent counterintuitive result emerges in relation to the alternative measure of technological opportunity used in the paper, i.e. APPSCIENCE. Such variable indeed is significantly and negatively related to all above-mentioned measures of sectoral patterns of innovation, except ENTRY. This result suggests that high technological opportunities can lead either to Schumpeter Mark II or Schumpeter Mark I pattern of innovations, depending on the specific features of knowledge behind such opportunities.

In the second place, all principal results concerning the significance and importance of industry characteristics hold whether or not other, more traditional, variables intended to capture the level of entry barriers – such as the ratio between industry turnover and total number of operating firms – are included in the specification. Third, tests of the joint significance of opportunity, appropriability and cumulativeness variables reject the null hypothesis, thus providing further confirmation of the important influence of industry characteristics on Schumpeterian patterns of innovation. Finally, the ratio of explained variance significantly increases when dummy variables are included in the specification to capture fixed-country effects, thus suggesting that the relationship between technological regimes and Schumpeterian patterns of innovation is fundamentally mediated by the specific features of each national system of innovation.

In conclusion, these results confirm that technological regimes, as represented by survey-based measures of technological opportunity, appropriability and cumulativeness conditions, have a very important and independent impact on the way innovative activities are structured across different industries.

FROM TECHNOLOGICAL REGIMES AND PATTERNS OF INNOVATION TO INDUSTRIAL EVOLUTION

Towards a theoretical explanation

The empirical evidence reviewed so far strongly supports the intuition that the patterns of innovation follow technology-specific paths: they are a function of some structural characteristics of the technology and – more generally – of some specific features of learning processes. At this stage, two major questions arise:

i) First, to what extent the notion of technological regimes can be used to explain not only the patterns of innovative activities but, more generally, the patterns of industrial dynamics? Indeed, insofar as innovation is a primary force of firm growth and industrial change, there ought to be a direct link between technological regimes and the patterns of industrial evolution.

ii) What kind of theoretical explanation can be given to these empirical results? How can we move from "reduced forms" to structural models of industrial evolution which make explicit the links between technological regimes and the observed patterns of industrial dynamics?

From an empirical perspective, evidence is now becoming available that technological regimes can indeed go a long way to account for the regularities observed in the dynamics of industries.

For instance, following Gort and Klepper (1982) and Winter (1984), Acs and Audretsch (1991) argue that sectoral differences in the patterns of entry and exit, in the relationships between size, age, growth and survival – and therefore, on firm size distribution – are to be accounted for by the nature of the relevant technology, defined in terms of accessibility of technological knowledge by firms external to the industry as opposed to incumbents. Acs and Audretsch find indeed econometric evidence that turbulence is higher, survival rates of young firms are lower and rates of growth of survivors are higher in industries characterized by an "entrepreneurial" as opposed to a "routinized" technological regime. The latter is defined as a technological environment characterized by high degrees of cumulativeness, appropriability and tacitness of the knowledge base.

Other studies (e.g. Baldwin, 1995) indirectly suggest that some broad characteristics of the learning processes of firms bear an important influence in determining market structure and its evolution over time. However, at this stage the evidence available at a disaggregated individual industry-level is not sufficiently developed to allow for firm conclusions. Clearly, here, much work needs to be done.

Moreover, these empirical findings still need to be thorougly backed and "explained" by theoretical models which should clarify the links between technological regimes and patterns of change. Indeed, even the direct evidence on the role of technological regimes in explaining the patterns of innovation and industrial dynamics is still based on reduced forms, rather than on well-defined structural models. Thus, a theory of industrial dynamics ought to be able to show that different functional representations of the mechanisms of access to innovation, and different parametrizations of variables like opportunity appropriability, cumulativeness, etc., can be mapped into different aggregate descriptions of industrial structures and industrial change. Moreover, an "evolutionary" approach would claim that different technological regimes affect primarily the processes of learning and market selection and that it would be misleading to simply project these intersectoral differences into some given, possibly sector-specific, "production function" to which agents try optimally to adjust.

After all, permanent opportunities of innovation imply that industry evolution occurs within an environment which is not functionally defined by scarcity, but in which technological discovery (and in general the creation of something new) is always possible. Highly imperfect appropriability mechanisms also imply the widespread existence of externalities and spillovers. Cumulativeness implies that increasing returns are a structural feature of industrial dynamics.

In this perspective, it has been suggested (Dosi and Orsenigo, 1988; Dosi, Malerba and Orsenigo, 1993; Dosi *et al.*, 1995) that the observed regularities and variety in the patterns of industrial dynamics can be accounted for by the consideration of the specific properties of learning (as proxied by technological regimes) and selection in any one industry. Admittedly, theoretical results in this respect are still less compelling as compared to empirical analysis. However, a growing body of theoretical exercises lends strong support to this claim.

Some models have tried to account for the observed patterns on the grounds of microfoundations resting on heterogeneous agents, imperfect learning and non-instantaneous market selection.

Others have attempted to explain some industrial regularities (e.g. firm size distributions and patterns of entry and exit) as an equilibrium outcome of a stochastic process of convergence to optimal techniques by rational agents under imperfect information. In particular Jovanovic (1982) assumes that new firms are continuously entering the industry, being unsure of their own productive efficiency. By producing, they acquire noisy information about their productivity. Those firms who discover that their efficiency exceeds their expectations expand their scale of output, while those who receive unfavourable signals contract or even exit. Thus, industry evolution is driven by noisy selection which fosters the growth of efficient firms and the decline of inefficient ones. Ericsson and Pakes (1992) have extended this model to consider the possibility that firms can affect their productivity by investing in learning (e.g. R&D) activities, the outcome of which is however random. In the same vein, other models (Lambson, 1991) examine industry evolution and try to account for some of the stylised facts discussed above as the result of changing exogenous market conditions.

In the evolutionary tradition, the seminal models by Nelson and Winter provided some basic reference for subsequent efforts. As known, Nelson and Winter's model was based on heterogeneous firms, characterised by different strategies of innovation and imitation and by different propensities to invest in innovative activities. Simulation exercises examined two different technological regimes: a "science-based" regime and a "cumulative" one. The models were actually able to generate different patterns of innovative activities and industry structures, yielding different measures of concentration and firm size distributions.

Developing on these lines, Silverberg (1987) and Silverberg, Dosi and Orsenigo (1988) provide further support to the idea that disequilibrium evolutionary models can generate ordered patterns of change, wherein certain key variables representing firm – and industry –specific learning regimes give rise to quite different patterns of evolution.

The basic structure of the latter models (and of more recent developments, reviewed below) builds on some firm-specific learning dynamics and on a replicator equation governing market selection and, thus, linking underlying regimes to the evolution of industrial structures.

Consider the dynamics of market shares as expressed by

$$\dot{f}_{it} = A\,[E_{it} - \bar{E}_t\,]\,f_{it}$$

where f_{it} is the market share of the i-th firm at time t;

$E_{it} = G\,[m_{it}\,]$ is the competitiveness of firm i – which in turn is a function of some vector of its technological and organizational characteristics m_{it}. $\bar{E}_t$ is the average competitiveness of the industry; and the dots stand for rates of change. The composition of the vector m, its changes over time and the G (.) function depend in principle also on the learning regimes of each industry. In stochastic versions, the learning mechanisms specific to each technological regime govern the transition probabilities in m_{it}.

In Silverberg *et al.* (1988), firms have to choose when to acquire a new production technology, the efficiency of which for the users improves with use. Part of these gains in efficiency, linked to phenomena like learning-by-using, etc., remain "private", meaning that they can be reaped only by those firms which actually use the new technology. Part of that knowledge, however, can become public, i.e. spill over to new adopters. Firms have therefore to decide the date of acquisition of the new technology, facing basically the trade-off between early acquisition, (with the possibility of gaining irreversible advantages *vis-à vis* competitors but also facing high degrees of uncertainty) and late acquisition (which might allow for lower uncertainty and exploitation of part of the experience of early adopters, but possibly accumulating too large a gap in efficiency) ([15]).

In this model, therefore, the technological regime is described by the opportunity conditions (the potential superiority of the new technology), appropriability conditions (the degree to which experience in the use of the new technology becomes public) and cumulativeness conditions (the degree to which the new technology improves with use). Simulations of the model actually yield not only "ordered" patterns of diffusion, i.e. a sigmoid diffusion curve as observed in the empirical analyses, but also different speeds of diffusion and differential rates of success between early and late adopters as a function of the two parameters expressing the "private" and the "public" rate of learning (i.e. cumulativeness and appropriability conditions).

([15]) In the model, firms' decisions concerning investment are governed by a desired payback period rule. Expectations with regard to the efficiency of the new technology are expressed by an "anticipation bonus", which is different among firms.

In Dosi and Salvatore (1992), industrial dynamics is explicitly examined, considering entry and exit as well as growth of firms. The model contrasts two extreme types of learning regimes. In the first one, the "Schumpeter Mark II" model, learning is cumulative. Thus, one assumes that i) the probabilities of exit decrease with the age of the firm (e.g. firms accumulate competences and competiveness over time); ii) the probability of exit decrease with size (e.g economies of scale in production, R&D, etc. are assumed); iii) the variance of growth rates decrease with age (e.g older firms are relatively more stable in the competences they incorporate and the market niches they occupy); iv) birth rates are proportional to the number of incumbents (as empirically suggested by Dunne, Roberts and Samuelson, 1988). The opposite occurs in the other extreme regime (the "Schumpeter Mark I" model), where no learning occurs, frequent discontinuities render the skills of incumbents obsolete, diseconomies of scale characterize production and R&D, etc.

In between these two extreme regimes, the model experiments with other intermediate conditions and studies firm size distributions which emerge over time in each of the archetypical "industries". The results indicate that indeed the sectoral distributions so generated depart significantly from a Pareto distribution. Clearly, this corroborates the conjecture that industry evolution is strongly influenced by the industry-specific regimes of learning and selection. However, a Pareto distribution is obtained as a result of a random aggregation over these different industrial archetypes, each characterized by different "technological regimes" and therefore different evolutionary processes. Such distribution tends to remain stable, as long as on average the learning (and selection) conditions do not dramatically change, as for instance in the case of a generalized "technological shock" (a change in some dominant technological paradigm) which devalues older competences and introduces a negative influence of age on growth.

Dosi *et al.* (1995) try to generalize the previous results, examining explicitly the processes through which firms accumulate competences.

Assume that "industry" (say, the equivalent in recorded statistics of 'aggregate manufacturing') is composed of several "sectors", each corresponding to particular technological and market regimes, which shall be defined below. In turn, any one "sector" is composed of "microsectors" (groups of relatively homogeneous products or technologies), loosely corresponding to the empirical analyses concerning "technological cycles". Hence, one has three levels of observation: most of the "action" – i.e. learning, changes in market shares, entry and exit – occurs within "microsectors"; but higher level statistical entities stochastically aggregate into "sectors" (i.e. regimes) and the overall "industry" (In fact, as we shall see, there is more than statistical aggregation since, in one of the regimes, firms may diversify across microsectors).

Each firm (j, if it is an incumbent; i, if it is an entrant) is defined by its age, a; size, s; and "competitiveness", e. Size and competitiveness are endogenous variables dependent on learning, market selection and – regarding size – also on the dynamics of the markets to which the firms belong. "Competitiveness" is a positive real number which in principle summarizes the technological and organizational capabilities of each firm. Hence, "learning" yields positive increments to firm-specific competitiveness.

The dynamic of structure of each "microsector" is endogenous and dependent on the processes described so far. However, we assume also a "demand cycle" which determines the absolute size of the microsector itself, which we take as exogenously given. The level of output (i.e. the size of demand) for microsector k at the beginning and the end of its "cycle" is conventionally set equal to unity and peaks at $T/2$ with $M^k_{\tau=T/2} = m$, where T is the total length of the "cycle"; we also assume that demand stays at unitary level thereafter.

New "microsectors" are randomly born every ω times (with ω uniformly distributed on a finite support).

Finally, it is assumed that in the regime "Schumpeter II" firms can cumulatively exploit their knowledge across different microsectors via entry and acquisition of incumbent firms.

Calling d, the event "diversification" of a firm from microsector k,

$$Pr\,(d = 1) = 1 - \theta \exp\left\{-\theta \frac{e^k_j}{\bar{e}^k}\right\} \tag{10}$$

More successful firms face a higher probability of diversification, while θ captures the degrees of intersectoral "serendipity" of knowledge.

If the event occurs, the microsector, l, toward which the firm moves is randomly drawn with a uniform distribution over all sectors. Next, the firm which is to be "acquired" or "founded" is selected, with uniform probability over all firms N^l of microsector l (if the firm drawn is an incumbent, then diversification occurs via "acquisition", otherwise it is an entry associated with establishment of a new unit – division' – in that market).

The model starts with n firms, identical in size and efficiency *(m)*. The latter grows over time via a learning dynamics which is different in various "regimes". In the first one (the "Schumpeter Mark I") model, incumbents do not learn. Evolution relies entirely on the entry of new innovators, the efficiency of which is given by

$$m_{i,t+1} = \bar{m}_t\,[1 + e_1] \tag{1}$$

where m_t is average efficiency of incumbents and e_I is a random variable drawn from a Poisson distribution with mean l (whose value captures the notional levels of innovative opportunities).

In the "Schumpeter Mark II" model, the learning regime is cumulative. That is, the dynamics of $m_{i,t}$ for incumbents is a Markov process:

$$m_{j,t+1} = \bar{m}_{j,t} [1 + e_I] \tag{2}$$

where the stochastic variable e_I is, again, drawn from a Poisson distribution specific to incumbents.

Learning by entrants is given by

$$m_{i,t+1} = \bar{m}_t [1 + e_E]$$

The birth of new firms is proportional to the number of incumbents, h:

$$b_{t+1} = n_t (h + k) \tag{3}$$

where k is a random variable uniformly distributed on some finite support.

Market shares, f_i, grow according to

$$\dot{f}_{i,t+1} = A\ [m_{i,t+1} / \bar{m}_{t+1} - 1] f_i \tag{4}$$

Finally, exit occurs whenever the firm's efficiency or market share falls under a certain threshold.

A crucial heuristic task of this type of simulation models (and in a sense their "validation") concerns their ability to generate some emergent aggregate properties and to allow some mapping of the latter into identifiable distributions of system parameters and micro characteristics. In fact, a rich set of properties, consistent with the evidence, appears.

First, the model generates aggregate statistics describing market structure, in term of number of firms, degrees of concentration, degrees of asymmetries and turbulence which are systematically different across the two learning regime, broadly in line with empiricial evidence. Specifically, the number of firms is typically higher in Schumpeter Mark I regimes and its number increases with the technological opportunities for entrants. Conversely, concentration is always a positive function of the opportunities for incumbents and a negative one of the opportunities for entrants. The latter are associated also with higher market turbulence (defined in terms of changes in market shares involving incumbents, entrants and exiters: $\Sigma_{i,j}\ |f_{(.)}(t+1) - f_{(.)}(t)|$) and higher interfirm asymmetries (as proxied by a measure of dispersion in the level of "competitiveness").

Second, some sort of life cycles, similar to those described by Gort and Klepper (1982) emerges at the level of "microsectors". Third, whenever such microsectors are aggregated in "industries" corresponding to particular industrial regimes, the expected relationships between age, size and growth emerge. For instance, in the "Schumpeter I industry", regressions of firms growth rates on age and size have a negative sign. Fourth, the nature of technological regimes exerts a primary influence on the average degrees of industrial concentration. Fifth, overall stochastic aggregation over "industries" (and "regimes") produces Pareto-type size distributions, which however hide a much greater underlying heterogeneity in the processes of corporate growth.

CONCLUSION

In this paper, it was argued that the nature of technological (and organizational) learning, interacting with the processes of market selection, define specific regimes of industrial evolution, which in turn generate empirically observable regularities: primarily, the Schumpeterian patterns of innovation Mark I and Mark II, but also specific industrial dynamics as revealed by varying degrees of turbulence, persistence of differentials in innovative performance and profitability, the relative stability of particular distributions in firms sizes over the whole population of manufacturing enterprises.

The empirical evidence accumulated on the existence of sectoral patterns of innovation that are different across sectors but rather invariant across countries and on the relationships between technological regimes and these patterns of innovative activities constitutes a promising starting point for more general empirical and theoretical analyses on industrial evolution.

While still admittedly in their beginnings, "evolutionary" interpretations of industrial dynamics hold the promise of accounting for a rather wide set of "stylized facts". They try to do so by identifying some robust correspondences between distinctive features of observable industrial dynamics on the one hand, and some underlying characteristics of the microeconomic processes of learning and market selection on the other.

Putting it in a biological metaphor, this research perspective suggests that explanations of industrial dynamics can be found in links between taxonomies on "species", on mutation processes and on selection criteria. We have still rather incomplete and rough evidence on all three sets of phenomena. And the theory joining them has yet to undergo stringent tests for robustness. But significant progress has been made over the last decade or two: more systematic evidence has been collected; the growing field of the economics of innovation has provided rich insights on micro learning processes; business economics has increasingly focused on the nature of problem-solving activities of firms and their related competences; and theoretical exercises on the properties of evolutionary processes are (slowly) spreading.

REFERENCES

ACS (Z.) and AUDRETSCH (D.B), 1990 — *Innovation and Small Firms*, Cambridge, (Mass.) MIT Press.

ACS (Z.) and AUDRETSCH (D.B.), 1989 — Small firm entry in US manufacturing, *Economica*, 56 (2), May.

ACS (Z.) and AUDRETSCH (D.B.), 1991 — Technological Regimes, Learning and Industry Turbulence, Berlin, mimeo.

ACS (Z.) and AUDRETSCH (D.B.), 1992 — New firm survival and the technological regime, *Review of Economics and Statistics*.

ALDRICH (H.) and AUSTER (A.), 1987 — Selezione naturale e strategie d'impresa, *Sviluppo e Organizzazione*, n° 103, October.

BALDWIN (J.), 1995 — *The Dynamics of Industrial Competition*, Cambridge, Cambridge University Press.

BEESLEY (M.E.) and HAMILTON (R.T.), 1984 — Small firms seedbed role and the concept of turbulence, *Journal of Industrial Economics*, 33, December.

BOND (R.), 1975 — Mergers and mobility among the largest manufacturing corporations, *Antitrust Bulletin*, 20, fall.

BRESCHI (S.), MALERBA (F.) and ORSENIGO (L.), 1995) — Technological regimes and Schumpeterian patterns of innovation, Bocconi University, mimeo.

COHEN (W.M.) and LEVIN (R.), 1989 — Empirical studies of innovation and market structure, *in*: SCHMALENSEE (R.) and WILLIG (R.) — *Handbook of Industrial Organization*, New York, North-Holland.

COHEN (W.M.) and LEVINTHAL (D.A.), 1989 — Innovation and learning: the two faces of R&D. Implications for the analysis of R&D investment, *Economic Journal*.

COLLINS (N.R.) and PRESTON (L.E.), 1961 — The size structure of the large industrial firms, *American Economic Review*, 51, December.

DOSI (G.), 1982 — Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change, *Research Policy*.

DOSI (G.), 1984 — *Technical Change and Industrial Transformation. The Theory and an Application to the Semiconductor Industry*, London, Macmillan.

DOSI (G.), 1988 — The microeconomic sources and effects of innovation, *Journal of Economic Literature.*

DOSI (G.), FREEMAN (C.), NELSON (R.R.), SILVERBERG (G.) and SOETE (L.), eds., 1988 — *Technical Change and Economic Theory*, London, Frances Pinter.

DOSI (G.) and MARENGO (L.), 1991 — Some elements of an evolutionary theory of organizational competences, *in* : ENGLAND, (R.W.), ed., *Evolutionary Concepts in Contemporary Economics*, University of Michigan Press, Ann Arbor.

DOSI (G.) and ORSENIGO (L.), 1988 — Coordination and transformation: an overview of structures, behaviour and change in evolutionary environments, *in*: DOSI (G.), FREEMAN (C.), NELSON (R.), SOETE (L.) and SILVERBERG (G.), eds., *Technical Change and Economic Theory,* London, Frances Pinter, 1988.

DOSI (G.), MALERBA (F.) and ORSENIGO (L.) 1993 — Evolutionary regimes and industrial dynamics, *in*: MAGNUSSON (L.), ed., *Evolutionary Approaches to Economics*, London, Kluwer.

DOSI (G.), MARSILI (O.), ORSENIGO (L.) and SALVATORE (R.), 1995 — Technological Regimes, Selection and Market Structure, *Small Business Economics.*

DOSI (G.) and SALVATORE (R.), 1992 — The Structure of industrial production and the boundaries between organization and markets, *in*: SCOTT (A.) and STOLPER (M), eds., *Pathways to Regional Development*, Westview Press.

DOSI (G.), TEECE (D.) and WINTER (S.), 1989 — Towards a theory of corporate coherence, mimeo.

DUNNE (T.), ROBERTS (M.J.) and SAMUELSON (L.), 1988 — Patterns of firm entry and exit in US manufacturing industries, *Rand Journal of Economics,* 19, pp. 495-515.

DUNNE (T.), ROBERTS (M.J.) and SAMUELSON (L.), 1989 —The growth and failure of US manufacturing plants, *Quarterly Journal of Economics*, 104, November.

ERICSON (R.) and PAKES (A.), 1992 — An Alternative Theory of the Firm and Industry Dynamics, Cowles Foundation discussion paper n° 1041, Cowles Foundation for Research in Economics at Yale University.

EVANS (D.S.), 1987a — The relationship between firm growth, size and age: estimates for 100 manufacturing industries, *Journal of Industrial Economics*, 35, June.

EVANS (D.S.), 1987b — Tests of alternative theories of firm growth, *Journal of Political Economy*, 95, August.

GEROSKI (P.A.), 1988 — The persistence of profits: a European comparison, *The Economic Journal.*

GEROSKI (P.A.) and MASSON (R.T.) (1987), — Dynamic market models in industrial organization, *International Journal of Industrial Organization.*

GORT (M.) and KLEPPER (S.), 1982 — Time paths in the diffusion of product innovations, *The Economic Journal.*

HALL (B.H.), 1987 — The relationship between firm size and firm growth in the US manufacturing sector, *Journal of Industrial Economics*, 35.

HANNAN (M.T.) and FREEMAN (J.) 1990 — *Organizational Ecology*, Cambridge (Mass), Harvard University Press.

HEIMLER (A.), MALERBA (F.) and PERETTO (P.), 1993 — Sources, appropriability and directions of technological change: the cases of the United States and Italy, *BNL Quarterly Review,* n° 185, pp. 225-242.

HIPPEL VON (E.), 1988 — *The Sources of Innovation*, New York, Oxford University Press.

HSIAO (C.), 1986 — *Analysis of Panel Data*, Cambridge, Cambridge University Press.

IJIRI (Y.) and SIMON (H.), 1977 — *Skew Distributions and Sizes of Business Firms*, Amsterdam, North-Holland.

JOVANOVIC (B.), 1982 — Selection and the evolution of industry, *Econometrica,* 50.

KAMIEN (M.) and SCHWARTZ (N.), 1982 — *Market Structure and Innovation*, Cambridge, Cambridge University Press.

KAPLAN (A.D.H.), 1964 — *Big Enterprise in a Competitive System*, Washington D.C., The Brookings Institution.

KESSIDES, 1990, *in* : MUELLER, 1990.

KLEPPER (S.), 1992 — Entry, exit and innovation over the product life cycle: the dynamics of first mover advantages, declining product innovation and market failure, paper presented at the International J.A. Schumpeter Society, Kyoto, August.

KLEVORICK (A.), LEVIN (R.), NELSON (R.) and WINTER (S.), 1993 — On the Sources and Significance of Interindustry Differences in Technological Opportunity, Cowles Foundation discussion paper n° 1052, Cowles Foundation for Research in Economics at Yale University.

LAMBSON (V.E.), 1991 — Industry evolution with sunk costs and uncertain market conditions, *International Journal of Industrial Organization*, 9.

LEVIN (R.), COHEN (W.M.) and MOWERY (D.), 1985 — R&D appropriability, opportunity and market structure: new evidence on some Schumpeterian hypotheses, *American Economic Review, Papers and Proceedings*, vol. 75,n° 2, pp. 20-24.

LEVIN (R.), KLEVORICK (A.), NELSON (R.R.) and WINTER (S.), 1987 — Appropriating the returns from industrial research and development, *Brookings Papers on Economic Activity*, 3.

MALERBA (F.) and ORSENIGO (L.), 1990 — Technological regimes and patterns of innovation: a theoretical and empirical investigation of the Italian case, *in*: HEERTJE (A.), *Evolving industries and Market Structures*, University of Michigan Press, Ann Arbor.

MALERBA (F.) and ORSENIGO (L.), 1993 — Technological regimes and firm behaviour, *Industrial and Corporate Change*, vol. 2, n° 1, 1993.

MALERBA (F.) and ORSENIGO (L.), 1995 — Schumpeterian patterns of innovation, *Cambridge Journal of Economics*.

MALERBA (F.) and ORSENIGO (L.), 1995a — On new innovators and ex-innovators, Universita Bocconi, Milano, 1995, mimeo.

MALERBA (F.) and ORSENIGO (L.), 1996 — Schumpeterian patterns of innovation are technology-specific, *Research Policy*.

MALERBA (F.) and ORSENIGO (L.), 1996a — The dynamics and evolution of industries, *Industrial and Corporate Change*.

MALERBA (F.), ORSENIGO (L.) and PERETTO (P.), 1995 — Persistence of innovative activities, sectoral patterns of innovation and international technological specialization, Universita Bocconi, Milano, 1995, mimeo.

MARCH (J.G.), 1991 — Exploration and Exploitation in Organizational Learning, Stanford University, mimeo.

MARENGO (L.), 1991 — Knowledge, Communication and Coordination in an Adaptive Model of the Firm, Roma, mimeo.

MERMELSTEIN (D.), 1969 — Large Industrial Corporations and Asset Shares, *American Economic Review*, 59, September.

MUELLER (D.), 1990 — *The Persistence of Profits*, Cambridge, Cambridge University press.

MOWERY (D.), 1983 — The relationship between the contractual and intra-firm forms of industrial research in American manufacturing, 1900-1940, *Explorations in Economic History.*

NELSON (R.R.), 1992 — *National Systems of Innovation*, Oxford University Press.

NELSON (R.R.) and WINTER (S.), 1982 — *An Evolutionary Theory of Economic Change*, Cambridge (Mass.), The Belknap Press of Harvard University Press.

ODAGIRI and YAMAWAKI, 1990, *in*: MUELLER, 1990.

PAVITT (K.), 1990 — Some foundations for a theory of the large innovating firm, Brighton, SPRU, University of Sussex, unpublished manuscript.

ROSENBERG (N.), 1976 — *Perspectives on Technology*, Cambridge, Cambridge University Press.

ROSENBERG (N.), 1982 — *Inside the Black Box*, Cambridge, Cambridge University Press.

SCHUMPETER (J.A.), 1912 — *The Theory of Economic Development*, Oxford, Oxford University Press.

SCHUMPETER (J.A.), 1942 — *Capitalism, Socialism and Democracy,* New York, Harper and Brothers.

SILVERBERG (G.), 1987 — Technical progress, capital accumulation and effective demand: a self-organisation model, *in*: BATTEN, CASTI and JOHANSSON (eds.), *Economic evolution and structural adjustment*, Berlin Springer Verlag.

SILVERBERG (G.), DOSI (G.) and ORSENIGO (L.), 1988 — Innovation, diversity and diffusion: a self-organisation model, *Economic Journal*, 98.

TEECE (D.), 1986 — Profiting from technological innovation, *Research Policy*, vol. 15, pp. 285-306.

TEECE (D.) and PISANO (G.), 1994 — The dynamic capabilities of firms: an introduction, *Industrial and Corporate Change.*

UTTERBACK (J.M.) and ABERNATHY (W.J.), 1975 — A dynamic model of product and process innovation, *Omega*, pp. 639-656.

WINTER (S.), 1984 — Schumpeterian competition in alternative technological regimes, *Journal of Economic Behaviour and Organisation*, vol. 5, n° 3-4, pp. 287-320.