CIDE

NÚMERO 46

Luis Enrique Arjona B.

TECHNOLOGICAL CHANGE AS AN EVOLUTIONARY PROCESS

Technological change as an evolutionary process

R E S U M E N

En este documento se revisa una serie de contribuciones de la literatura sobre el cambio tecnológico que son afines a una perspectiva evolutiva. El propósito central del documento es reunir a dichas contribuciones dentro de un marco conceptual que sea útil para analizar el desarrollo de tecnologías específicas y de las industrias asociadas a las mismas.

A B S R A C T

In this this paper we review a series of contributions from the literature on technological change that are akin to an evolutionary approach. The main purpose of the paper is to put together this contributions in a conceptual framework that is useful for the analysis of the development of specific technologies and of their associated industries.

Technological change as an evolutionary process

Introduction

The theoretical and empirical research on technological change is one of the research traditions that has made the most significant contributions to the emergence of the evolutionary approach to economic theory. In this paper we draw on a number of these contributions in order to build the theoretical framework that can be used for the empirical analysis of technological change. Since the term "evolutionary" has spread considerably in recent times and is often used in works that have little in common regarding their theoretical perspective; we start by stating briefly, in section 1, what in our view the main tenets of an evolutionary approach are. In sections 2 to 4, we have made a selective review of concepts and ideas from the literature on technological change. Our purpose has been to articulate those ideas in a framework that is useful for the empirical study of specific technologies. Our review of the literature has been based on two criteria. First, that the concepts could be made operational for empirical analysis. Second, that the concepts and propositions were consistent with the evolutionary approach. Finally, section 5 states the basic ideas of an evolutionary analysis of technological change.

1. The evolutionary approach in economics

The central concern of the evolutionary perspective is to explain economic change. It sees the economy as a complex evolving system, which is open in the sense that the outcomes of its development are not predictable. The diversity and mutability of the different components of the system and the pressure exerted on them by selective forces that emerge both from within and from outside the system are the fundamental elements shaping the course of economic change.

There is a major difference between the evolutionary approach and the equilibrium perspective that dominates most of economic analysis. The later looks at the way in which the actions of independent agents coordinate and sees no inherent tendency to change in the economy. In evolutionary thinking, in contrast, the economy is seen as a system in continuous change and the problem is to understand the mechanisms by which it changes.

While discussing the evolutionary approach in economics it is useful to compare it with the application of evolutionary ideas in biology, since the latter offers an invaluable source of concepts and analogies, given the more advanced degree (at both the theoretical and the empirical level) to which evolutionary explanations have been used in biology.[1]

In economics as in biology, evolution is seen as primarily driven by two mechanisms: one that introduces novelty in the system and creates variety, and

---

[1] There are, however, limits to the extent to which one can make use of biological analogies in economic and social sciences. This is due not only to the fact that the theory of evolution in biology remains a highly controversial subject (See Mani, 1991), but also because of the specificities of socioeconomic systems that arise from their eminently human nature.

another that selects on the diversity of the entities within the system. At the more general level, in the social domain, one may think of habits and routines as an equivalent to genes, and of the mechanisms that provoke changes in them as the analogue of those behind genetic variation. Regarding the mechanisms of selection, the institutional settings of economic systems (and at a more basic level the natural environment itself), will act in favour or against the behaviour (of individuals and organizations) associated with those routines. In this way, selection will change the diffusion of routines and modes of behaviour in populations of individuals and organizations. According to this idea, which has been traced back to Veblen, socioeconomic evolution is seen "...as a selection process working on institutions as units of selection".[2] The essential element that supports this analogy is that routines, as genes, are depositories of information and transmit it: actions and thoughts are sustained and structured by routines and habits that operate on behaviour as a set of instructions.

As in the natural world, diversity is an essential element for selection to operate, and the generation of diversity is fundamental for evolution. However, in contrast with biological evolution, in which genetic variation occurs at a slow pace, in human systems the introduction and spread of novelty take place at a much faster rate. The difference with respect to the natural world is not only a question of speed. In economic systems, the mechanisms that generate variety play a much more important role in driving the evolutionary process. The innovative and imitative activities that create and modify habits, routines and institutions are, above all, the result of purposeful behaviour. The fact that we are dealing with individuals and organizations with intentions, which acquire and interpret information and are capable of thinking and learning, is a central element that distinguishes evolution in economics from that in biology. New behaviour seeks, in general, to be adaptive. Therefore, the environment influences the process of creation of variety. Furthermore, individuals and organizations not only innovate keeping the present conditions of their environment in mind, but also anticipating changes in it.

Routines, as genes, replicate themselves. However, in routines there is not a clear physical mechanism like that of genetic duplication. There is, instead, a social mechanism that involves imitation and learning. As many authors have pointed out, there is an important Lamarckian element in socioeconomic evolution.[3] Adaptive behaviour is learned and fixed in routines carried in the memory of individuals and organizations. These routines are transmitted from one generation to the next and play an important role on shaping subsequent behaviour.

Regarding the selection environment, it is important to stress not only that it affects the creation of variety by influencing its direction, but also that the introduction of new routines and behaviour produces changes in the environment itself. The implications of these have been summarized by Allen and

[2] Hodgson (1993), pp. 126, 132.

[3] See Matthews (1984), Clark and Juma (1987) and Hodgson (1993).

Lesser by noting that "...evolution generates diversity and diversity drives evolution."[4]

The most important specificity of evolution in human systems is the institutional dimension that is found in all components involved in the process of selection: objects, forces and environment.[5] Economic evolution takes place at different levels. The process can be observed at the level of technologies, firms, industries, market structures and other socioeconomic institutions, and at the level of the economic systems as a whole. At all these different levels it is possible to identify the emergence and extinction of new and old forms. A key concept, on which the theory of evolution in biology elaborates at the different levels of analysis, is that of species. There is not, however, an equivalent concept in economics.[6] Taxonomic classifications in economics have to follow, thus, a different logic, one that is appropriate for the different levels at which evolution takes place. The concept of institution, broadly defined as "...commonly held patterns of behaviour and habits of thought, of a routinized and durable nature, that are associated with people interacting in groups or larger collectives...",[7] is a fundamental concept. This concept cannot only be the basis to elaborate relevant taxonomies at different levels of evolution, but it may also serve to establish links between these different levels. Furthermore, organizations, as materialized and organized forms of institutions,[8] are elementary units on which to base the population approach that is essential for evolutionary analysis. The criteria by which a population can be defined may vary according to the specific purposes of the analysis and there is no need, as in biology, to tie ourselves to a single concept like that of species.

2. Technology and the definition of industry

The definition of technology used in this work is a broad one. Technology includes the material elements employed and obtained in the process of production, the individual and collective knowledge and skills of the people who participate, and the elements of organization that articulate them. Thus, we depart, from the interpretation of technology that limits the concept to its artifacts dimension by defining it as the set of techniques available for the production of a specific good.[9]

---

[4] Allen and Lesser (1991), p. 165.

[5] The market, which acts as the selection environment, is an institution and is itself supported by a set of institutions that facilitate and regulate the exchange of commodities. See Hodgson (1988).

[6] Matthews, (1984).

[7] Hodgson (1993), p. 253.

[8] Johnson (1988).

[9] That is, our concept of technology is broader than the traditional input-output approach of classical and neoclassical economics. Our interpretation of technology also differs from reformulations of this approach which subsume knowledge, skills and organizational elements under the all purpose category of inputs. (See, Gomulka (1990), pp. 4-6).

The distinction between techniques and technology is important. A perspective of technology that overlooks its human and institutional elements is simply inconsistent with the analysis of technological change as an evolutionary process. The changes that one observes at the level of artifacts are only one aspect of more fundamental changes in the knowledge base, skills and decision rules of both the individual and institutional elements of the organization that deploys a technology.

While recognizing the knowledge dimension of technology, it is also important to distinguish technology from science. As E. Layton has pointed out, "the rules of science refer to nature and the rules of technology refer to human artifice. The function of technology is to provide a rational basis for design, not to enable man to understand the universe."[10]

It would be equally wrong to look at science as producing the knowledge and at technologists as merely applying it. The relationship between science and technology is better described as a dialogue in which each contributes to the development of the other. Sometimes, advances in technology precede scientific discovery and pose problems that require scientific explanation; in other occasions, scientific discoveries do provide de spark for invention and innovation.

The three dimensions of technology

When looking at technology it si useful to distinguish between three dimensions of it that overlap in different degrees, namely, the knowledge, the routine and the artifact dimensions of technology. The distinction between these three dimensions and an understanding of how they interrelate constitutes a major source of insights into the analysis of technological change. In general, it is at the level of artifacts, i.e. in the techniques, where the manifestation of technological change is more evident. However, to assess the significance of such changes, to understand the process by which they come about and to identify the determinants of their rate and direction, it is necessary to look into the parallel changes that occur at the level of knowledge and routines.

The existing devices that one identifies with technology are the materialization of the achievements of specific problem-solving activities. Particular kinds of knowledge underlie behind these activities: theoretical and practical, codified and tacit, which provide the rational basis for the design of products and their related processes. This problem-solving oriented knowledge is intimately associated with the satisfaction of human needs and with the values of society.

The final element in our triad is what we have denominated routines. The term routine is used in a broad sense as habits of thought, skills and practical courses of action held individually and collectively within the organization that deploys a technology. These routines consist of ensembles of decision rules, which express themselves in individual and collective skills and procedures.

---

[10] E. Layton (1974) p. 40.

The representation of technology in a characteristics space

The artifact dimension of technology relates to a transformation process in which energy and materials of one form are added value by transforming them into energy and materials of a different form.[11] The higher economic value of the products of this transformation process is obviously related to, and dependent on, the fact that they respond to the satisfaction of needs for which there is will and capacity to pay.

When a specific technology is considered at this level, three aspects of it are made evident, namely, the transformation process itself, its product, and the services that the latter provides to its user. On this basis, as Saviotti and Metcalfe have proposed, it is possible in principle to characterize technologies by representing each of these three aspects by means of interrelated multidimensional characteristics vectors. This framework can be used to give a detailed description that informs us about how characteristics of the process translate into the technical characteristics of the product and how the latter relate to performance.[12]

The paradigmatic character of technology

The knowledge dimension of technology refers to a body of concepts and theories that enable the design and operation of the process of production. This knowledge conforms to an understanding of the process, of its relationship with the needs it satisfies and (of fundamental interest to us) of potential directions for further development of the technology. This last idea has been advanced in different ways by researchers in the area of technological change.[13] Dosi has expressed it through the generic notion of technological paradigm that he defines as a "'model' and a 'pattern' of solution of *selected* technological problems based on *selected* principles derived from natural sciences and on *selected* material technologies...[which] ...embodies strong presumptions on the *directions* of technical change to pursue and those to neglect"[14] (stress in the original).

The recognition of this, less visible, aspect of technology is crucial in the study of the behaviour of the individuals and organizations involved in the evolutionary process of technological change.

Routines, learning and inertia

Organizations compete by deploying specific technologies. There are two important aspects of the routine dimension of these technologies. First, the formation of routines is essential for the command of such technologies and for

---

[11] Metcalfe and Boden (1991), p. 710-711.

[12] Saviotti and Metcalfe (1984).

[13] Rosenberg's (1976) "focusing devices", Sahal's (1981a,1981b, 1985) "technological guideposts", Nelson and Winter's (1982a) "technological regimes" and Dosi's (1982) "technological paradigms" are concepts very close in meaning which have been put forward to capture this idea.

[14] Dosi (1982), p. 152.

the mere existence of the required individual and collective skills and problem solving strategies. The routine dimension of technology is essential for the functioning and effectiveness of the organization that articulates the production process. The formation of habits of thought, action, interaction and communication are an integral part of the learning process and a requisite for the mere existence of the individual skills and of the collective competence of the organization. The emphasis on both the individuals and the organization is important since, paraphrasing Henderson and Clark, the skills and knowledge of individuals translate within the organization into a collective competence, while the organization itself is defined in terms of a set of communication rules.[15] From this perspective, the specific technology that an organization commands can be characterized, following Nelson and Winter, as a (complex) routine.[16]

The second important aspect of routines is the element of inertia that they carry with them. Technological change involves, in general, modifications in components of that routine and their re-articulation in a new coherent routine. There are, however, limits to the extent and speed at which the organization can make such changes without losing its framework of reference and ceasing to be effective.[17] Inertia is essential in preserving variety and is of fundamental importance for the evolutionary process, since for the selection mechanism to operate, variety has to be stable relative to the speed with which selection operates.[18]

Technology as a system

A final point that is important to stress is the systemic nature of technology. In words of Sahal, "...a system is characterized by the multilateral interdependencies between its parts. That is to say, a system is an *ensemble harmonique*. Thus, the parts of a system unlike those of an aggregate, acquire their characteristics from the whole."[19] This systemic nature is present in the different dimensions and aspects that we have reviewed. A technology constitutes a working whole in which all the elements that we have mentioned are combined. The different elements that integrate a technology in their knowledge, artifact and routine dimensions, only acquire full meaning and become functional as articulated components of the technology system.

A technology based definition of industry

The concepts above allow us to think about technology at different levels of abstraction. The focus on the knowledge dimension and the use of concepts like that of technological paradigme, for instance, can be applied from the level of

---

15 Henderson and Clark (1990).

16 Nelson and Winter (1982a).

17 Clearly, routines are not the only elements that introduce inertia. Factors like sunk costs, contracts, and other kind of commitments operate in the same direction.

18 Metcalfe (1989), p. 57, 62.

19 Sahal (1981b), p. 4, n. 1.

a specific technology as it exists within a firm, to the level of general fields of technology that apply to whole branches of economic activity. In order to make our theoretical framework operative for empirical analysis, it is necessary to distinguish between these different levels of abstraction.[20]

At the most most concrete level we can think on technology as it exists within an individual firm. Technologies are firm specific. Firms compete on the basis of specific designs and develop capabilities to be effective in the context in which they operate. As the argument in section 1 suggested, this diversity at the industry level plays a central role in the evolutionary process.

To refer to technology at a more general level, we will introduce Nelson and Winter's concept of technological regime,[21] interpreted as a basic design, that is, a set of basic design parameters associated with key aspects of a specific technology. The cognitive element of this concept has been emphasized by Metcalfe and Boden. Following these authors, a technological regime is seen as consisting of a "hard core of fundamental scientific and engineering principles" adhered to by a group of firms, which gives coherence to their technological activities. Thus, adherence to such principles defines a firm as belonging to the population of firms working on that regime.[22]

The concept of technological regime leads us immediately to the question of the definition of industry that is appropriate to our purposes. By industry, we will understand here the population of business organizations that carry on the production and the commercialization of the products associated with the technological regime within which all operate. [23] Therefore, the industry is a population of business units that is defined by the technology that is common to all of them. Although we will be using the terms firm and business unit interchangeably, it is necessary to emphasize that our concept of firm is more restricted than the meaning conveyed by the every day use of the word. The firm-business unit equivalence will normally hold only for small enterprises; modern firms are usually an aggregation of business units within a larger organization.[24] All business units within an industry share the common knowledge base defined by the technological regime and also show some resemblance in other dimensions of their technologies such as artifact and skills involved in the production process and other routines within the organizations.

Finally, it is possible to move to an intermediate level of abstraction

---

[20] See Hagerdoorn (1989), pp. 95-98

[21] Nelson and Winter (1982a).

[22] As Metcalfe and Boden note, "While these principles may be subject to elaboration over time, they are beyond question as agreed principles held in common by all business units operating within the regime." Metcalfe and Boden (1991), p. 714.

[23] The definition of industry used here is of course arbitrary; different criteria can be used to render an equally valid definition. The merit of our definition rests, thus, on its usefulness for the purposes of the present analysis.

[24] Metcalfe and Boden (1991), p. 710.

between the notion of technological regime and the specificity of each firm's technology and distinguish a relatively small number of competing design configurations within an industry. These design configurations are different "operational routes" to the design and production of specific artifacts.[25] They are a set of particular technological solutions to the problems defined by the regime, which have emerged, diffused and survived in the industry. In this context, each of the specific technologies of individual firms in an industry will be found to correspond to one of these design configurations.[26] The notion of design configuration is a key concept; it allows us to deal with diversity and helps to highlight similarities and differences in the technological routines of the firms.

Competing firms innovate and develop existing designs. They create market niches and may introduce new design configurations and, in this way, they increase variety.[27] Imitation operates in the opposite direction and tends to create similarity. However, the pervasiveness of diversity is evident for any casual observer. Inter-firm differences go beyond those in their technologies; their sources are varied: the structure of the firm and its links (when this applies) with larger organizations, its history, and ultimately the diversity at the level of the individuals that constitute the firm. These differences are at the basis of the different behaviour and market performance of the firms that drive the evolution of the industry.

3. Technological change and the development of an industry

In the previous section we presented a framework that allowed us to characterize a technology and its associated industry. The discussion there was, most of the time, of a static flavour. However, to use the term static when talking about technology is almost a contradiction. In this section we move on to discuss technological change and we focus on the specific question of the co-evolution of a technology and its industry. In what follows, we make a selective review of some of the main ideas of the literature of technological change regarding the evolution of technology and its associated industry.[28]

A landmark in most of the theoretical and empirical work on technological change, since the early studies of the 1950s to the present day, has been the focus on the major breakthroughs that mark the birth of new industries. Independently of whether or not these innovations are the direct object of study, their role as point of reference is widespread in the literature on technological change. Traditionally, these innovations have been termed "radical". Here we

---

[25] Metcalfe and Boden (1991), pp. 714-715.

[26] See Georghiou et. al. (1986), p. 33-35.

[27] In some occasions, a firm may even break with the mould established by the regime of the industry to which she belongs and open the possibility of the development of a new industry.

[28] Surveys of the literature of technological change are found in Gomulka (1990), Stoneman (1983) and Coombs et. al. (1987). On innovation, see Binswanger and Ruttan (1978) and Dosi (1988). On diffusion, see Metcalfe (1988).

take a radical innovation as our starting point. Our purpose is to highlight the most relevant aspects of its evolution on the basis of the framework presented in previous sections. In our opinion, the analysis of technological change and the assessment of its significance is often hampered by two problems. First, a lack of precision in establishing the relationship between the concepts of industry and technology. Second, insufficient attention to the knowledge and routine dimensions of technological change and to the way in which they relate to the changes observed at the level of artifacts. It is hoped that the framework presented in this document will move us towards overcoming these problems.

On the interrelation between innovation and diffusion

A most important achievement of the research on technological change has been its contribution to a clearer perception of the relationship between innovation, diffusion and industrial development. Recent research has called our attention towards three important facts. First, that innovation is a rather continuous process that plays an important role in shaping the process of diffusion of a technology, while the latter modifies the conditions on which further innovation takes place.[29] Second, that the environment in which a technology develops is continuously shaped and to a certain extent created, by the processes of innovation and diffusion themselves.[30] Both the technological and the economic aspects of the immediate environment relevant to the industry are greatly influenced by the patterns of innovation and diffusion.[31] Finally, and of particular interest to us, is the fact that the firms themselves and the characteristics of the industry co-evolve with the technology.

There are two major streams in the literature of technological change that have converged in the exploration of these issues. The first is the study on the relationship between the life cycle of a technology and that of its associated industry. The second is the research on innovation and diffusion of innovation in the Schumpeterian tradition. In the following three subsections we present very succinctly the main ideas of these two lines of research in relation to the co-evolution of technology and industry. Later in the paper we attempt a synthesis based on these two streams of literature in order to discuss the factors that determine the rate and direction of technological change.

The life cycle of a technology

The product life cycle hypothesis rests, as the term suggests, on the analogy with the life cycle of living organisms in biology. Among the earliest proponents of this idea were Muller and Tilton who noted that new industries where created by the occurrence of major innovations and developed as less

---

[29] See Georghiou et. al. (1986), p. 79.

[30] See Amendola and Gaffard (1988), Amendola and Bruno (1990).

[31] See Freeman (1990), Hagerdoorn (1989) and Georghiou et. al (1986).

radical innovations were introduced.[32] The life cycle hypothesis was also present in the writings of Vernon and Hirsch on international trade.[33] The basic idea is that of a pattern of development which follows a series of stages: birth, growth, maturity and decline. From the perspective of the innovation and diffusion aspects of technological change, the life cycle expresses itself in two superimposed patterns of innovation and diffusion. With respect to innovation, the early stage represents a fluid period with frequent changes in the design of the product and of its associated process. This is followed by a tendency to standardization. This is a stage in which the emphasis shifts towards process innovations that seek to exploit economies of scale and reduce costs. A slow down in innovative activity characterizes the mature stage. Finally, the decline phase is in general related to the emergence of a new technology that displaces the old one. Regarding the process of diffusion that runs in parallel, the pattern followed during the life cycle can often be approximated by an S-shaped trajectory, which can be observed in different measures of market penetration. That pattern represents the different rates at which such penetration occurs during the introduction, growth and maturity phases. Less research has been done on the pattern followed by declining industries but it suggests that decline would follow an inverted S pattern.[34]

The basic scheme presented above has been subsequently refined as empirical research has brought to the surface additional elements. A first issue is that the sharp dichotomy between product and process innovation has proven to be inadequate. In some cases it may be useful to think of product and process innovations as separate. However, there are instances, such as cost reduction innovations that relate to the use of new materials, which convey significant changes in both process and product design.[35]

A second question is that, as several authors have pointed out, the biological metaphor can be in many cases misleading. There may be changes in the economic environment, or significant innovations within the regime, which can be the basis for dematurity and for a reversal in the slow down of the diffusion of a technology. A pattern of diffusion different to the S shaped pattern may result from these changes.[36] Furthermore, during its diffusion, the technology changes, different designs compete in the market and new generations of artifacts displace old ones. Thus, the path of diffusion of a technology that one observes is, in a sense, an aggregate of curves corresponding to different design configurations.

The question of the maturity is central to the analysis of the evolution of a technology and of its industry. There are limits to how much a given

---

[32] Muller and Tilton (1969)

[33] Vernon (1966) and Hirsch (1967).

[34] See Chapman (1991) and Markusen (1985).

[35] Sahal (1985).

[36] See Iwai (1984a, 1984b), Abernathy and Clark (1985), Nelson (1992), Durand (1992).

technology can be improved.[37] It is important to bear in mind the limits defined by a technological regime when judging innovations in order to distinguish whether we can talk of dematuration or, rather, of the emergence of a new regime. Another important consideration is that, as Georghiou et. al. have pointed out, maturity is also largely a socio-economic phenomenon. It depends on the collective expectations of those involved in developing a technology with respect to the profitability of attempting further developments.[38] The dematuration that has occurred in some industries after economic changes like the oil shocks of the 1970s and also with the effect of pervasive new technologies such as microelectronics illustrates the fact that both technological and socioeconomic aspects are at the basis of the phenomenon of maturity.

The dominant design hypothesis

The emergence of a dominant design is a theme intimately related to the life cycle idea. According to the dominant design hypothesis, the "fluid" period in the development of a technology, characterized by active experimentation in product technology, comes to an end with the emergence of a dominant design.[39] This dominant design incorporates a number of basic choices that are not reviewed any more in subsequent designs but are only further refined and elaborated upon.[40] Following Clark, the emergence of a dominant design can be characterized as the introduction of a well fitting design that receives market ratification and clarifies aspects of the consumer environment. As a result, items of the research agenda once opened become closed and development follows along narrowing lines.[41] As presented above, the image created by this story is one of superiority of the dominant design which imposes over competing alternatives. However, as Nelson has noted, there are other stories about the way in which a dominant design becomes established.[42] There is the possibility of "locked-in" phenomena, brought about either by the concentration of resources on a design that leads to increasing returns or, in technology systems, by early starts that create switching costs derived from interrelatedness and networking with other technologies.[43] This gives room for factors different to strict technological merit, such as small events and chance, to play a role in the establishment of a dominant design.[44]

The dominant design hypothesis has received confirmation by a number of

---

[37] See, for instance, Sahal's (1981a, 1985) discussion on the fact that increases in the size of an object require, after a certain point, if it is to remain functional, a qualitative change that alters its morphology and structural properties.

[38] Georghiou, et. al. (1986).

[39] Abernathy and Utterback (1978), Clark (1985), p. 246.

[40] Henderson and Clark (1990), p.14.

[41] Clark (1985), p. 246.

[42] See Nelson (1992).

[43] See Arthur (1988) and David (1985).

[44] See for instance David and Bunn (1990).

case studies which, as Utterback and Suárez note, have been limited to assembly products.[45] Studies of industries like automobiles, tractors and aviation illustrate the convergence of different manufacturers towards a number of basic design concepts, which leads to the standardization of the product and to the passage to a new stage in the life cycle of the technology.

The dominant design hypothesis is a source of valuable insights; however, its universality is still open to question,[46] at least as it is applied to the typical cases mentioned above. Part of the problem lies in the fact that the hypothesis has been stated, in most cases, in terms of the product or the industry rather than as the technology life cycle idea that we have presented here. In technologies such as chemical processing, it is often the case that the innovations do not rest so much in the product itself but in the process. A good example of this is the Haber-Bosh process for the synthesis of ammonia.[47] Another example is polyethylene, which had been synthesized long before the introduction of ICI's high pressure process. In the chemical industries, the search for processes with high yields and based on cheap and relatively abundant raw materials have been central to innovation. This suggests that, if the dominant design idea were to apply at all in such cases, it would have to focus more on process rather than on product design. A second consideration is the fact that scaling up in these industries is a process that is central from the outset. Thus, the idea that the emergence of a dominant design precedes the stage in which innovative emphasis is put on achieving economies of scale does not follow in the way it does for assembled products.

Independently of the question of the universality of its applicability, the concept of dominant design offers useful guides for the analysis of the development of technology. This idea can be directly related to the concept of design configuration of the theoretical framework presented earlier in this chapter. There may be different designs coexisting in an industry. A single dominant design may emerge in some cases with complete or virtual elimination of others, but this will not necessarily happen in every industry. One reason for this is that markets are not homogeneous and different configurations may enjoy advantages in different niches. Another reason is the diversity that is inherent to the industry. Nonetheless, independently of whether a single design imposes itself or more than one coexist, the general idea of some configurations being abandoned while elements of design become firmly established with the development of a technological regime seems to be a plausible generalization.[48]

---

[45] Utterback and Suárez (1993), p. 2.

[46] See Nelson (1992).

[47] See Haber (1971), pp.85-97.

[48] These elements of design which become established relate to Sahal's concept of technological guide posts. Sahal (1981a, 1981b). In the present context, the concept will be applicable in some cases to the technological regime as a whole, while in others it will be specific to some design configurations.

The parallel development of the technology and the industry

A first aspect of the relationship between the development of a technology and that of its industry is the connection of innovation and diffusion with the phenomena of industrial growth and decay. This aspect was identified long ago by Burns and Kuznets in their work on industrial development.[49]

A second issue is the relationship between technological change and industry structure. Most of the literature addressing this issue has focused on the influence of market structure on innovation taking the former as given, in order to explore the validity of the so called Schumpeterian trade-off.[50] Here we will focus on the opposite line of causation, which is more relevant for our present enquiry. The life cycle approach to technological change has thrown some light on this issue. In most industries, the trend in the early years of its existence is one of active entry which, as the life cycle hypothesis suggests, is also one of intense experimentation with the technology. There is some evidence that the emergence of a dominant design has a noticeable impact on the number of firms in the industry. Utterback and Suárez have found that, in a number of industries, this entry was followed by a decline in the number of participants, which appears to be associated with the changes in their respective technologies.[51] After the appearance of the dominant design, it is sound to expect this effect: first, because those firms strongly attached to unsuccessful configurations by sunk investment in knowledge and physical and managerial capital will, in general, find it difficult to switch to the dominant design; second, because the change toward more emphasis in cost reduction suggests that the new stage of the cycle will require different firm capabilities than those of the early stage, and not all firms will be able to develop them. The same argument will apply in a more general scenario in which the new stage in the development of the industry is marked not only by a reduction in the number of competing designs but a similar trend in other aspects of the process. Thus, concentration and market growth tend to generate an oligopolistic market structure as the industry moves towards maturity. However, the picture of a secular trend towards oligopoly is inaccurate. Firstly, because it will not necessarily apply to all industries: considerations on the relationship between plant scale and market size, which will not be pursued here, have an important bearing on this. Secondly, because, as we mentioned above, the innovation that follows the introduction of a new technology is an important part of its development and may have a significant impact on market structure. Swan and Gill, in their study of various industries experiencing rapid innovation, have found evidence in the sense that significant innovations within an industry may have concentrating or de-concentrating effects depending on whether they show continuity or they break with the widespread views held in the industry about the

---

[49] Burns (1934), Kuznets (1954).

[50] A survey of this literature can be found in Kamien and Schwartz (1975, 1982); for a critical discussion of this literature, see Nelson and Winter (1982b).

[51] Utterback and Suárez (1993).

future development of the technology.[52]

Competition, selection and the co-evolution of technology and industry

The evolutionary approach offers a rich theoretical framework to integrate the ideas presented above. The emergence and evolution of a technology and of its associated industry are shaped in a competitive process in which the driving forces are selection and the generation of variety. In this context, the ability of competitors to adapt, to anticipate to the conditions of the market and to exploit the development potential of their design configurations that they champion is the key aspect for their competitive performance, rather than their static allocative efficiency. Firms search for competitive advantages by, among other things, introducing technological improvements. At each point in time, market demand and price structure act both as devices that guide innovative activity and that exert selective pressure. In this way, they favour some routes of technological development and hamper others. The routine dimension of technology and the elements of inertia in them play an important role. In the competitive process, some design configurations are eliminated; firms that, by chance or judgment, had stuck to successful designs tend to be in a more favourable competitive position. The different success of competing firms translates in different profitability and growth. For some firms, repeated failure will eventually lead to bankruptcy. For others, there will be scope for adaptation and they will be able to survive. Seen under this light, the size and number of firms in an industry and the diffusion of different routines among them are all outcomes of the same evolutionary process that drives technological development.

Not only technology and market structure change; the selection environment is not immutable: innovation and diffusion redefine the conditions under which subsequent market selection will take place. Moreover, those changes are not always unintended and in some cases they are deliberately promoted by firms participating in the industry. To some extent, the development of a technology is also a process of creation of its environment.[53] Firms and customers learn, and the concept of product and user needs are formed and reshaped.[54] There is, thus, the broader issue of the formation of the industry and its context. The co-evolution of the institutions relative to an industry is a complex process that involves not only the firms, but institutions such as governmental agencies, universities, engineering associations, regulations.[55]

---

52 Swan and Gill (1993).

53 Amendola and Gaffard (1988), p. 14.

54 See Clark (1985) and Durand (1992).

55 Pérez (1983).

4. The measurement and assessment of technological change

It is at the level of artifacts where technological change is more apparent, and this is the natural place to look at when one is searching for measures of its pace and direction. On the other hand, the knowledge and routines dimensions are crucial for the assessment of technological change. They can serve to build taxonomies which bring to light different aspects of the process of technological change.

Measurement of innovation and diffusion

The distinction between the innovation and the diffusion aspects of technological change is useful for measurement purposes. The characteristics space framework described in section 2 can be used to describe the changes experienced by a technology and to register the emergence of new characteristics that may appear during its development. The way in which this can be done has been suggested by Hagerdoorn: by selecting generations of key elements of the technology, it is possible to make operational concepts like that of technological trajectory.[56] This way of proceeding can be useful in the construction of diagrammatic representations of the evolution of a technology.[57]

Regarding diffusion, on a first approximation, it can be measured by indicators such as number of firms, output, capacity or employment associated with the technology. It is more problematic, however, to construct analytical indicators which relate actual to potential penetration of the technology. As Nasbeth and Ray note, it is practically impossible to define unambiguously the denominator of this type of measures.[58] The potential number of adopters and the notional point of saturation are not only difficult to identify, but will change with the evolution of the technology.

Indirect measures of technological change based on input indicators such as R&D expenditure or on output indicators like patents or publications of scientific papers have also been widely used in inter-sectoral comparisons. When referred to specific industries within a sector, they have been used to give an indication of the pattern followed by the rate of growth in the knowledge associated with that industry. This can be extremely useful to identify the trends in the technology side of the life cycle. Walsh, for instance, analyses the different stages in the cycle of a number of chemical industries on the basis of such type of indicators.[59] The use of expert opinion about which have been the most significant additions to a technology has also been used for a more qualitative follow-up of the evolution of a technology.[60]

---

[56] Hagerdoorn (1989).

[57] See for, instance, Abernathy and Clark (1985) and Durand (1992).

[58] Nasbeth and Ray (1974), p. 297.

[59] Walsh (1984).

[60] A study of chemical industries that combines both approaches is that of Achilladelis et. al. (1990).

Assessing the significance of innovations

Radical innovations

In our analysis we have proceeded by assuming an initial radical innovation and the birth of an industry. One of the objectives here is to determine when we can say that this kind of innovation has taken place. In the XIX century and early XX century, it was relatively common to see new industries starting virtually from nothing under the impulse of innovators-entrepreneurs.[61] However, in the modern times of large corporations with R&D facilities, innovation is more and more the result of the activity of these firms.[62] Increasingly, what we have called "new industries" emerge from established firms. Thus, it is not always easy to distinguish between a new technology and the mere launching of a new product in an already established industry.[63]

In our framework, independently of issues related to the impact of the innovation in the market, the critical question is whether the innovation breaks with existing technological regimes. It is existing technologies that can provide the point of reference to judge whether or not an innovation qualifies as radical. Thus, a clear definition of the principles and core elements of design that define a regime is essential. There is not a clear-cut rule on this issue; the definition of a regime rests to a great extent on technical judgment about what is the heart of a technology. A focus on the three dimensions of technology can help in this endeavour. As a first approximation, the main clues on what defines a regime can be found in the generic descriptions, in the literature of a specific technology, about what the product is, its applications and how it is produced. As we have repeatedly emphasized, changes at the level of artifacts will be associated with corresponding changes in the other dimensions of the technology. New artifacts will also involve new technological knowledge which will often be noticeable as a new entry in the description of technologies within the broader field to which they belong.

Innovation and the competitive process

As it stands, the discussion above about whether an innovation qualifies or not as radical is relevant mainly in relation to the consistency of our framework. Taxonomies of innovations, however, can be analytically useful and different criteria will shed light on different issues. Sahal, for instance, classifies innovations from the point of view of their relationship with the technological constraints associated with the design as structural, material or system innovations.[64]

Technological change, we have argued, is shaped in the competition between firms that innovate, not only developing their own design configuration but, more generally, searching for new technology and market opportunities. A focus on how

---

[61] See Jewkes, et. al. (1958).

[62] See Freeman (1982).

[63] See Nelson (1992), pp. 8-9.

[64] Sahal (1985), p. 64.

innovations relate to the actors that participate in this process is essential for an understanding of technological change. This directs our attention to the knowledge and routine dimensions of technology.

A number of scholars have converged in recent years in placing the competence of the firm as the point of reference to define criteria for the classification of different kinds of innovation.[65] The concept of competencies incorporates the three dimensions of technology as they exist in the physical and human resources of a specific firm. Other non-technological capabilities, which are relevant for the competitive position of the firm, such as marketing and financial capabilities, are also contemplated in the concept of competence. However, technology occupies a central place. Abernathy and Clark, and Tushman and Anderson have proposed to distinguish between innovations according to whether they are competence enhancing or competence destroying. As these authors have shown, enquiring about the effects of an innovation on different competencies can enhance considerably our understanding of the significance of an innovation in relation to the competitive process.[66] Along these lines. Henderson and Clark, in particular, have introduced the concept of architectural innovation. This concept is applied to those innovations that, without necessarily changing the components of a product, modify the way in which they are integrated into the system. Architectural innovations according to them have a destructive effect on the knowledge and communication channels of firms and have significant competitive implications.[67]

In general, the advantages of a competence based appraisal of changes in technology are, first, that it highlights elements associated with the impact that they are likely to have for competition within the industry; and second, that they bring into focus the knowledge and routine aspects of technology which tend to be hidden and, in doing so, they inform us about the new conditions, the possible sources and directions of subsequent technological change.

Moving further in this direction, Metcalfe and Boden have introduced the concept of strategic paradigm.[68] This concept directs our attention to the active role of firms in changing their selective advantages. In particular, it expresses how in each firm the synthesis between the prescriptive content of the technological regime, the firm assessment of its own competencies and its objectives, is articulated to produce the firm's technology strategy. This concept of strategic paradigm brings us closer to an understanding of the factors that guide the innovative and growth efforts of the firms. Along this line, Swan and Gill emphasize the presumptions of the firms with respect to the future tendencies in the technological regime and how they relate to the firms' competencies. They introduce the notion of "visions of the future" which is seen

---

[65] Among the recent literature that focuses on firms competencies or capabilities see Tushman and Anderson (1986), Dosi, Teece and Winter (1992), Henderson and Clark (1990), Prahalad and Hamel (1990).

[66] Abernathy and Clark (1985), Tushman and Anderson (1986).

[67] Henderson and Clark (1990).

[68] Metcalfe and Boden (1991).

as defining "the range of technological and market outcomes for which the organization can be prepared."[69] The impact of an innovation on the competitiveness of the firms in the industry will depend on the degree in which that innovation departs from those firms' visions.

Technological change and the pervasiveness of a technology

An important dimension of technological change is its overall economic impact. This, we have argued, materializes through the process of diffusion and post-innovation development. Although, the pattern that a technology will follow in its evolution cannot be predicted in advance, nor can the size of its market niche be anticipated with precision, the position of a technology with respect to other technologies and its relationship with them is a source of valuable indications of its economic potential. Firstly, because an innovation will compete with technologies with similar performance characteristics. Thus, this can give us an idea of the magnitude of its prospective market niche. Secondly, because the position of a technology in the economic system and the degree to which key elements of its knowledge base are shared with other technologies is fundamental for its impact on the economy. In this context, Freeman and Pérez have proposed a taxonomy that distinguishes between four different levels of pervasiveness in technological change: incremental innovation, radical innovation, new technology systems and changes in techno-economic paradigm.[70] In the context of the foregoing argument, incremental innovations would be equivalent to the changes within existing regimes which we have been analysing. The term radical innovation has basically the same meaning that we have given to it here. It is the other two concepts that are of interest to our present discussion. New technology systems refer to constellations of technological and economically interrelated innovations. The synthetic materials, petrochemicals and plastics industries are some examples.[71] The concept of techno-economic paradigm is associated with changes that affect almost every branch of the economy. Such a paradigm consists of many clusters of radical and incremental innovations and may embody several new technology systems. Following Schumpeter, Freeman and Pérez associate these changes with the long waves observed in economic development.[72]

Although the scope of the present work is limited to the analysis of +individual technologies, the taxonomy mentioned above calls our attention to the fact that the position of an innovation with respect to wider changes in technology is an important aspect to be considered when assessing their potential significance. Thus, in the analysis of individual technologies, considerations of interrelatedness may be of great importance. A good example is found in David and Bunn study of the development of the electricity supply industry. There, the

---

69 Swan and Gill (1993), p.24.

70 Freeman and Pérez (1988), see also Pérez (1983) and Freeman (1988).

71 Freeman and Pérez (1988).

72 Freeman and Pérez (1988).

authors analyse innovations within network technologies. In this type of innovations, interrelatedness is all important, as David and Bunn illustrate very neatly with the case of the rotary converter.[73]

A final useful conceptualization related to the relationship between technologies is the notion of fusion and fission of technologies.[74] The former captures the idea that sometimes new technologies result from the confluence of existing technologies. The notion of fission refers to new technologies that emerge in the course of the development of a technological regime, which draw heavily on its knowledge base, but split from that regime.

5. The rate and direction of technological change

In this final section, we bring together the ideas presented earlier in the paper in order to outline the main elements that are involved in an evolutionary analysis of technological change.

The Supply-demand approximation to technological change

The analysis of innovation and diffusion has traditionally been based implicitly or explicitly on a supply-demand perspective. Thus, it is convenient to outline briefly the main characteristics of this approach.

A supply-demand framework centres our attention on two fundamental questions: first, the willingness and capacity to pay for the products of a technology, and, second, the profitability of producing them. In that context, innovation will be determined, on the demand side, by those factors affecting customer needs and their valuation of the different characteristics of the product. On the supply side, what is relevant for innovation are the constraints and opportunities associated with the technology and the cost and uncertainty of undertaking innovative activity.

Regarding diffusion, demand factors relate basically to the creation and growth of the market niche; questions of information and learning by users are all important. Clearly, specific considerations will change depending on whether the potential user is a final consumer or another firm that would use the innovation in its own production process. The first case is one where subjective valuation and purchasing power will determine whether or not to buy the commodity and how much of it is bought. The second case depends on profitability considerations, which affect the adoption decisions of the different firms concerned; subjective consumer consideration only enter indirectly in this second case. Supply factors, in turn, also involve questions of profitability, which affect the decisions of the firms about pricing, quantities to be produced and capacity expansions. Factors affecting entry considerations will also be relevant for supply and diffusion.

Curiously, in early research on both innovation and diffusion, the role of supply factors tended to be neglected, leading to a "demand pull" perspective of

---

[73] David and Bunn (1990).

[74] See Sahal (1985) and Kodama (1986, 1992).

innovation and to models of diffusion, which looked only at the behaviour of adopters. Recent research on both fronts has vindicated the equally important role of supply.[75]

An evolutionary perspective of technological change

The supply-demand scheme, as outlined above, offers a convenient way of analysing the factors that affect innovation and diffusion in terms of how they affect the behaviour of producers and buyers, and is quite illuminating. Our purpose, however, is to analyse the role of those factors in the context of the competitive process that shapes the development of technology. Diversity, the mechanisms that generate it and market selection are central to that process. From that point of view, a supply-demand perspective, which focuses on representative agents and equilibrium outcomes resulting from the interplay of supply and demand forces, is not the most adequate. Thus, we will proceed by analysing the factors that affect innovation and diffusion in relation to the technology, the industry and the environment.

The technology

At any point in time, the technological regime that defines an industry consists of a body of knowledge not only about the properties of the artifacts and their design, but also about puzzles that remain to be solved, and notions of which improvements and directions of research seem promising and worth attempting and which do not. Each design configuration defines a more specific agenda of its own according to the particular solutions to design problems that it represents. These notions about the possible routes for the development of the technology are product of its past trajectory. During the development of a technology, design configurations emerge and are abandoned and guide posts are left for subsequent development.[76] These guide posts take the form of design principles about how sets of process and product characteristics can be delivered. They involve a perception of what can be improved and at what costs, and of what trade-offs are likely to emerge among the multiple characteristics of the technology.

Inherent to the concept of design is the fulfilment of some needs. At any point in time there will be a lower and an upper bound of performance characteristics delivered by the technology. The concept of technological corridor has been proposed by Georghiou et. al. to refer to the trajectory in time of this band. The corridor also plays a role in guiding the development of the technology in terms of the range of performance that is expected across the different characteristics that define the technology.[77]

---

[75] The most influential work leading to the 'demand pull' perspective of innovation was that of Schmookler (1966). For a critical view of this perspective, see Mowery and Rosenberg (1979). Among the early demand oriented studies to which we make reference are those of Griliches (1957) and Mansfield (1961). On the more recent work which emphasizes the role of supply factors, see Metcalfe (1981) and Stoneman and Ireland (1983).

[76] Sahal (1981a, 1981b)

[77] Georghiou et. al. (1986).

Thus, regime, designs and corridor, together, point to the broad direction which the development of a technology may follow. Dosi has used the metaphor of a tunnel, rather than a line, to convey the idea of the large number of possibilities defined by the prospective technological trajectory.[78]

The state of development of the technology is not only relevant for the direction but also for the rate at which change is likely to take place. The state of knowledge and the extent to which the possibilities opened by the regime in its development have been explored, will have an important impact on the magnitude and frequency with which innovations are likely to take place. Particular attention has been drawn to the fact that, eventually, decreasing returns will appear in the innovative effort: the advance of a regime will become more difficult as the limits of its potential are approached. This phenomenon is referred to, in the literature, as "Wolf's law".[79] Of course, there will also be exogenous factors such as relevant scientific discoveries and advances in related technologies, which may have an impact on the technology and relax some of the difficulties, making it easier, for some time, to achieve further advance in the regime.

The firms and competition within the industry

A key characteristic of industries is diversity. Firms differ not only in the design configurations that they promote, but in a number of other things such as their size, being (or not) part of a larger organization and, of fundamental importance, in their competencies. The competitive behaviour of firms rests on a series of competencies: technological, financial and marketing, which are at the heart of their different market performance. The differences in the technological competence of the firms are of particular interest to us. This competence is defined by the specific way in which the technology exists within the firm, that is, the collective knowledge and skills that are articulated in its technological routine. The differences in technological competence are at the basis of the different capacity of firms in identifying and exploiting technological opportunities. The routines and accumulated knowledge of firms are both an asset and a liability: they are the foundation for the effectiveness of their performance but may also operate as barriers, limiting the opportunities that are perceived and the capacity to change in certain directions.

Therefore, the design configuration in which a firm operates and its technological competence will exert a major influence on both the direction and effectiveness of its efforts to develop the technology. Clearly, there are a number of other factors that also intervene, such as other non-technological competencies, business objectives, financial position, the perception of the intensity and the main areas of competition (including threats of entry) and the overall perception of the market environment. In each firm, the impulse to innovate, imitate and grow responds to the elaboration of the firm's technology and growth strategies, which will involve an assessment of all the different

---

[78] Dosi (1982).

[79] See Georghiou et. al. (1986), p.25.

aspects just mentioned. Central to the elaboration of that strategy will be the possibilities opened by the technology. These will set the alternatives from which, on a broader assessment, the strategy of the firm will emerge to guide the magnitude and direction of the innovative efforts and its capacity expansion.[80]

The distribution of firms according to their size and to the design configurations that they promote, the specific strategies that the firms follow and their ability to carry them affect the rate and direction of technological change. They influence the distribution of innovative efforts and the relative economic weight acquired by the different designs, and give shape to the process of diffusion.

Two additional remarks are in order. First, that other factors such as non-programmed creativity, contingencies and the influence of small events may have a significant influence on the outcome of firms' behaviour and, thus, have an unsuspected effect on the course of technological development. Second, it is important to keep in mind that, while developing the technology, firms develop themselves: some competencies are enhanced, knowledge accumulates, skills and overall routines are modified. At the same time, other possible courses of development are abandoned. In this way, the new conditions for further technological development are set.

The selection environment

The environment plays two fundamental roles in the development of a technology: it acts as the mechanism of selection and also a source of inducement. Ultimately, it is the selection environment that determines the relative success of firm's diverse behaviours. The artifacts (the goods and services produced) are the direct objects of selection. This determines the differential profitability of firms and, through it, their growth. It is through the effect on the development of the firms in the industry that the mechanism selects indirectly over the knowledge and routine dimensions of technology, which are, in evolutionary terms, the "replicators". In this way, the economic significance of the technology and, in particular, that of the different design configurations is altered.

Two basic elements of the selection environment are the overall growth of the market and the users valuation of the different performance characteristics of the products of the different designs in the industry, not only relative to each other but also with respect to substitutes from other industries. Here, the considerations made earlier about whether buyers are consumers or other firms, apply. It is important to emphasize that these valuations will be influenced by the current state of both competing and complementary technologies.

Not only the objective characteristics of the products are important for the process of diffusion. Equally important are the questions related to information and learning by potential users and to the different factors that may create inertia and lead buyers to stick to other technologies.

---

[80] This relates to the Metcalfe and Boden's notion of strategic paradigm discussed in section 4.

A third aspect of the selection environment relates to the quality, price and availability of inputs. This will affect the cost of the firms and the price and performance that the firms themselves will be able to deliver. It is worth mentioning, in passing, that the fact that, as Sraffa's famous book reminds us, commodities are produce by means of commodities,[81] adds complexity to the problem of analysing technological change. In the development of an industry, division of labour will often break a technology into subsystems, redefining the industry and giving way to associated sub-industries. In a way, this is as if firms where able to buy competencies in the market. These considerations have to be kept in mind in empirical analysis.

Needless to say, the environment consists also of other institutions: government agencies, legislation, professional groups and other institutions relevant to the industry being analysed. These may also have a direct influence on the rate and direction of technological change.

Another important characteristic of the selection environment is its myopia: it selects on what exists. This, as we have already mentioned, may lead to lock-in phenomena in which design configurations, which are seen as technically inferior to other alternatives, become the dominant ones. Because of increasing returns or networking considerations, a technology can become dominant by getting an early foothold in the market.

The second role of the selection environment is that of inducing technological change. This inducement role is grounded on the same aspects that its selective role. The different sources of selective pressure are taken into account by the firms in their decisions concerning innovative efforts, pricing, production and capacity expansions. Firms try to adapt to the environment and to anticipate its changes. Moreover, to the extent that they are able to do so, they try to modify the environment in their favour. Thus, the boundaries between firms and their environment are not clear-cut. This, as Metcalfe and Boden have noted, rather than weakening the evolutionary argument gives ground for an enriched discussion.[82]

Three final comments are in order before closing our discussion on the selection environment. First, that the environment is not immutable: it is changed by the development of the technology. Prices, the information that buyers have of the product and their valuations change and create the new conditions in which further development can take place. Second, that the environment relevant to the industry will be subject to shocks that may have profound effects on the rate and direction of change of the technology. Finally, regarding international trade, the national characteristics of the environments and their implications for the capacity of firms to compete internationally will be central for the geographical diffusion of technology and for patterns of international trade.

---

[81] Sraffa (1960).

[82] Metcalfe and Boden (1991), p. 710.

6. Concluding remarks

The main purpose of this paper has been to put together a series of contributions from the literature on technological change, in a conceptual framework that can be applied to the empirical analysis of specific technologies. A first step in the analysis of the development of an industry is to try to distinguish the key elements that define its technological regime, and to identify the different design configurations that compete in the market. Another important step in the analysis is to look at the histories of the technologies in order to identify the main factors that have shaped the course of their development. In order to explain such development, we have proposed to analyse those factors in the context of an evolutionary process rather than in an equilibrium framework.

The analysis of innovation and diffusion has traditionally been based implicitly or explicitly on a supply-demand perspective. Thus, the factors that affect technological change are grouped according to whether they correspond to the demand or the supply forces of the market. This way of proceeding offers a convenient way of analysing the factors that affect innovation and diffusion in terms of how they impinge on the behaviour of producers and buyers, and has produced many valuable insights. However, it has a major shortcoming: it makes us look at these phenomena from an equilibrium perspective, as the market coordinated outcome of the interplay between two forces acting relatively independently from each other. The perspective that we adopted here was to look at the factors that influence technological change as relative to three key elements of the evolutionary process: the technology itself, the population of firms, and the selection environment. This way of proceeding has the advantage that it unveils another dimension of the way in which these factors operate, namely, through the mechanisms that generate variety and through the mechanism of selection.

References

Abernathy, W. J. and Clark, K. B. (1985) 'Innovation: Mapping the winds of creative destruction', *Research Policy*, 14, pp. 3-22.

Abernathy, W and Utterback J. M. (1978) 'Patterns of innovation in technology', *Technology Review*, 7, pp. 40-47.

Achilladelis, B.; Schwarzkopf, A. and Cines, M. (1990). 'The dynamics of technological innovation: the case of the chemical industry'. *Research Policy*, 19, pp. 1-34

Allen, P. M. and Lesser, M. (1991) 'Evolutionary human systems: Learning, ignorance and subjectivity' in Saviotti, Paolo and Metcalfe, Stan, *Evolutionary Theories of Economic and Technological Change: Present Status and Future Prospects*. Harwood Academic Publishers, pp. 160-171.

Amendola, M. and Bruno, S. (1990) 'The behaviour of the innovative firm', *Research Policy*, 19, pp. 419-433.

Amendola, Mario and Gaffard, Jean-Luc. (1988). *The Innovative Choice. An Economic Analysis of the Dynamics of Technology*. Basil Blackwell.

Arjona, Luis (1994). *Essays on the Study of Technological Change and International Trade*. Unpublished Ph.D. thesis, University of Manchester, Faculty of Economic and Social Studies.

Arthur, B. (1988). 'Competing technologies: an overview'. In G. Dosi, et. al.

(eds.). (1988)., pp. 590-607.
Binswanger, A. and Ruttan, V. (1978). *Induced Innovation. Technology Institutions and Development*. Baltimore, Johns Hopkins University Press.
Burns, Arthur F. (1934) *Production Trends in the United States since 1870*. New York, National Bureau of Economic Research.
Chapman, Keith. (1991) *The International Petrochemical Industry. Evolution and Location*. Basil Blackwell.
Clark, K. B (1985) 'The interaction of design hierarchies and market concepts in technological evolution', *Research Policy*, 14, pp. 235-251.
Clark, Norman and Juma, Calestous. (1987) *Long Run Economics: an evolutionary approach to economic growth*. London, New York, Pinter Publishers
Coombs, Rod; Saviotti, Paolo P. and Walsh, Vivien (1987). *Economics and Technological Change*. Totowa, N.J., Rowman and Litlefield.
David, P. A. (1985). 'Clio and the economics of QWERTY'. *American Economic Review*, 75(2), pp. 332-7.
David, P. A. and Bunn, J. A. (1990). 'Gateway technologies and the Evolutionary dynamics of network industries: lessons from the electricity supply history'. In A. Heertje, and M. Perlman (eds.). (1990). *Evolving Technology and Market Structure. Studies in Schumpeterian Economics*. University of Michigan, 1990, pp. 121-163.
Dosi, G. (1982) 'Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change', *Research Policy*, 11, pp. 147-162.
Dosi, Giovanni; Freeman, Christopher; Nelson, Richard; Silverberg, Gerald and Soete, Luc (eds.). (1988). *Technical Change and Economic Theory*. London, Pinter Publisher.
Dosi, G.; Teece, D. J. and Winter, S. (1992). 'toward a theory of corporate coherence'. In G. Dosi, R. Giannetti and P. Toninelli (eds.). (1992). *Technology and Enterprise in a Historical Perspective*. Oxford, Clarendon Press, pp. 185-211.
Durand, T. (1992) 'Dual technology trees: Assessing the intensity and strategic significance of technological change', *Research Policy*, 21, pp. 361-380.
Freeman, Christopher (1982). *The Economics of Industrial Innovation*. Second Edition, London, Frances Pinter (Publishers).
Freeman, C. (1988). 'Diffusion: The spread of new technology to firms, sectors, and nations'. In A. Heertje, (ed.). (1988). *Innovation, Technology and Finance*. Basil Blackwell, pp. 38-70.
Freeman, C. (1990) 'Diffusion: Spread of new technology to firms, sectors, and nations' in Heertje Arnold (ed.) *Innovation, Technology and Finance*. Basil Blackwell, pp. 38-70.
Freeman, C. and Perez, C. (1988) Structural crisis of adjustment: business cycles and investment behaviour. In Dosi, et. al. (eds.) *Technical Change and Economic Theory*. London, New York, Pinter Publishers, 1988. pp. 38-66.
Georghiou, Luke; Metcalfe, J. Stanley; Gibbons, Michael; Ray, Tim and Evans, Janet. (1986) *Post-Innovation Performance: Technological Development and Competition*. London, MacMillan.
Gomulka, Stanislaw. (1990). *The theory of technological change and economic growth*. London, New York, Routledge.
Griliches, Z. (1957). 'Hybrid corn: and exploration in the economics of technological change'. *Econometrica*, 25(4), pp 501-522.
Haber, Fritz L. (1971). *The Chemical Industry 1990-1930. Internal Growth and Technological Change*. Oxford, Clarendon Press.
Hagerdoorn, John (1989) *The Dynamic Analysis of Innovation and Diffusion: A Study in Process Control*. New York, London, Pinter Publishers.
Henderson, R. M. and Clark, K. B. (1990) 'Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms', *Administrative Science Quarterly*, 35, pp. 9-30.
Hirsch Seev (1967) *Location of Industry and International Competitiveness*. Oxford, Clarendon Press.
Hodgson, Geoffrey M. (1988) *Economics and Institutions. A Manifesto for a Modern Institutional Economics*. Cambridge (Engl.), Polity Press.
Hodgson, Geoffrey M. (1993) *Economics and Evolution. Bringing Life Back into Economics*. Cambridge (Engl.), Polity Press.
Iwai, K. (1984a). 'Schumpeterian dynamics. An evolutionary model of innovation and imitation'. *Journal of Economic Behaviour and Organization*, 5, pp.

159-190.
Iwai, K. (1984b). 'Schumpeterian dynamics, part II. Technological progress, firm growth and "economic selection"'. *Journal of Economic Behaviour and Organization*, 5, pp. 321-351.
Jewkes, John; Sawers, David and Stillerman, Richard. (1958). *The Sources of Invention*. London, MacMillan.
Johnson, B. (1988) 'An institutional approach to the Small-Country Problem, in Freeman, C. and Lundvall, B. (eds.), *Small Countries Facing the Technological Revolution*. London, New York, Pinter Publishers, pp. 279-297.
Kamien, M. I. and Schwartz, N. L. (1975). 'Market structure and innovation; a survey'. *Journal of Economic Literature*, 13, pp. 1-37
Kamien, Morton I. and Schwartz, N. L. (1982). *Market Structure and Innovation*. Cambridge, Cambridge University Press.
Kodama, F. (1986). 'Japanese innovation in mechatronics technology'. *Science and Public Policy*, 13(1), pp. 44-51.
Kodama, F. (1992). 'Technology fusion and the new R&D'. *Harvard Business Review*, July-August, pp. 70-78.
Kuznets, Simon (1954) *Economic Change. Selected Essays in Business Cycles. National Income and Economic Growth*. London, William Heineman Ltd.
Layton, E. (1974) 'Technology as knowledge', *Technology and Culture*, 15, pp. 31-41.
Mani, G. S. (1991) 'Is there a general theory of biological evolution?', in P. Saviotti and J. S. Metcalfe (eds.), *Evolutionary Theories of Economic and Technological Change: Present Status and Future Prospects*. Harwood Academic Publishers, pp. 31-57.
Mansfield, E. (1961). 'Technical change and the rate of imitation'. *Econometrica*, 29(4), pp. 741-766.
Markusen, A. R. (1985) *Profit Cycles, Oligopoly and Regional Development*. Cambridge, MIT Press.
Matthews, R. C. O. (1984). 'Darwinism and economic change'. In Collard, D. et. al. *Economic Theory and Hicksian Themes*. Oxford, Oxford University Press, p. 91-117.
Metcalfe, J. S. (1981). 'Impulse and diffusion in the study of technical change'. *Futures*, 13(5), pp. 347-359.
Metcalfe, J. S. (1988). 'The diffusion of innovation: an interpretative survey'. In G. Dosi, et. al. (eds.). (1988), pp. 560-589
Metcalfe, J. S. (1989) 'Evolution and Economic Change', in Silberston, A. (ed.), *Technology and Economic Progress*. MacMillan, pp.54-84.
Metcalfe, J. S. and Boden, M. (1991) 'Innovation strategy and epistemic connection: An essay on the growth of technological knowledge', *Journal of Scientific and Industrial Research*, 50, Oct., pp. 707-717.
Mowery, D. C and Rosenberg, N. (1979). 'The influence of market demand upon innovation: a critical review of some recent empirical studies'. *Research Policy*, 8, pp. 103-153.
Muller, D. and Tilton, J. (1969) 'Research and development as barriers to entry', *Canadian Journal of Economics*.
Nasbeth, L. and Ray, G. F. (eds.). (1974). *The diffusion of new processes. An international study*. Cambridge University Press
Nelson, Richard (1992) *The Co-Evolution of Technology and Institutions*. Columbia University, September, (mimeo).
Nelson, R. and Rosenberg, N. (1993). 'Technical innovation and national systems'. In R. Nelson (ed.). (1993). *National Innovation Systems*. New York, Oxford. Oxford University Press. 1993, pp. 3-21.
Nelson, Richard and Winter, Sidney (1982a). *An Evolutionary Theory of Economic Change*. Cambridge Mass., Cambridge University Press.
Nelson, R. and Winter, S. (1982b). 'The Schumpeterian tradeoff revisited'. *American Economic Review*, 72(1), pp. 114-132.
Perez, C. (1983) 'Structural change and the assimilation of new technologies in the economic and social system'. *Futures*. Vol. 15, No. 5, pp. 357-375.
Posner, M. V. (1961) 'International trade and technical change', *Oxford Economic Papers*, 13(3), pp. 323-341.
Prahalad C.K and Hamel G. (1990). 'The core competence of the corporation'. *Harvard Business Review*, 68(3), pp. 79-91.
Rosenberg, Nathan. (1976) *Perspectives on Technology*. Cambridge, Cambridge University Press.

Sahal D. (1981a). *Patterns of Technological Innovation*. Addison Wesley, Reading (Mass.).

Sahal D. (1981b). 'Alternative conceptions of technology', *Research Policy*, 10, pp. 2-24.

Sahal D. (1985) 'Technological guideposts and innovation avenues', *Research Policy*, 14, pp. 61-82.

Saviotti, P. P. and Metcalfe, J. S. (1984) 'A theoretical approach to the construction of technological output indicators', *Research Policy*, 13, pp. 141-151.

Schmookler, Jacob (1966). *Invention and Economic Growth: Data and Selected Essays*. Cambridge (Mass.), Harvard University Press.

Sraffa, Piero (1960). *Production of Commodities by Means of Commodities*. Prelude to a Critique of Economic Theory. Cambridge, Cambridge University Press.

Stoneman, Paul (1983). *The Economic Analysis of Technological Change*. Oxford University Press.

Stoneman, P. and Ireland, N. J. (1983). 'The role of supply factors in the diffusion of new process technology'. *Economic Journal*, (supplement), 93, pp. 65S-77S.

Swan, Peter and Gill, Jas (1993). *Corporate vision and rapid technological change: the evolution of market structure*. London, Routledge.

Tushman, M. and Anderson, P. (1986). 'Technological discontinuities and organizational environments'. *Administrative Science Quarterly*, 31, pp. 439-465.

Utterback, J. M. and Suárez, F. F. (1993) 'Innovation, competition, and industry structure', *Research Policy*, 22, pp. 1-21.

Vernon, R. (1966) 'International investment and international trade in the product cycle', *Quarterly Journal of Economics*, 80(2), pp. 190-207.

Walsh, V. (1984) 'Invention and innovation in the chemical industry: Demand-pull or discovery-push?, *Research Policy*, 13, pp. 211-234.