ON THE LIFE CYCLE OF KNOWLEDGE INTENSIVE SECTORS

Thomas Grebel

University of Augsburg, Germany

Jackie Krafft

CNRS-GREDEG and OFCE-DRIC, France

Pier Paolo Saviotti

UMR GAEL, CNRS-GREDEG and OFCE-DRIC, France

The theme of industry life cycle (ILC) is today one of the central fields of research in industrial dynamics. ILC shows that industries behave like biological organisms, and proceed through different phases of development, from emergence to decline. Although this approach constitutes one of the most important recent advances in industrial dynamics, its major results are drawn from the historical evolution of industries that emerged during the first half of the 20th century in the US. In this perspective, we stress that these results relative to industries which are today mature industries are not necessarily generalisable to the evolution of industries that emerged (or radically changed) during the late 20th century, such as the biotechnology and the telecommunications industry that are often termed as knowledge intensive industries. We thus elaborate on the new theme of knowledge intensive industry life cycle.

JEL Classification: L20, L65, L96.

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thomas.grebel@wiwi.uni-augsburg.de
jackie.krafft@ofce.sciences-po.fr
pierpaolo.saviotti@ofce.sciences-po.fr

1. Introduction

The discovery that many industrial sectors have a life cycle is one of the most important advances in industrial economics of the last twenty years. The most frequently observed regularity defining the industry life cycle (ILC) is the pattern of change in the number of firms in the industry. There are other regularities, such as the changing balance between product and process innovation, but they occur with lower frequency. Studies of the dynamics of a number of both pre-existing and new industrial sectors for the period following the 1980s show the emergence of a number of new phenomena not previously detected in the ILC. These new phenomena, the most notable of which are the survival of incumbents (Large Diversified Firms or LDFs), the regular entry of new firms (New Technology Firms or NTFs), and finally the co-existence of NTFs and LDFs within Innovation Networks (INs), seem to be more frequent in knowledge intensive sectors. The objective of this paper is to discuss whether the ILC model needs to be modified to account for these new phenomena, and eventually how.

Based on the apparent anomalies detected in recent observations about the evolution of industrial sectors we start to study the role played by knowledge in industrial dynamics. We argue that the type of knowledge that was created and diffused in different historical contexts had a decisive impact on the organisation of industry. Going back to the core definition of industrial dynamics, that is, to the study of the forces that brought about the current organization of the industry and of how they have changed over time, we investigate how historical trends in the generation and diffusion of knowledge have shaped the dynamics of the industry (Section 2). Following Chandler (1962, 1977) and Langlois (2003) we argue that the capitalist economic system underwent two transitions, the first from the early industrial economy to the *visible hand* (Chandler), the period (~1900-1970s) during which large, vertically integrated corporations emerged and changed from the U to the M form type, and the second, called the *vanishing hand* (Langlois), when the reverse trend towards vertical disintegration started taking place (Section 3). In our point of view, the type of ILC studied in the literature belongs uniquely to the period of the visible hand. In other terms, although cyclical phenomena occur in different periods, we cannot expect the ILC to be the same during the visible and the vanishing hands. The main reason for this is that the transitions first to the visible hand and later to the vanishing hand are determined by a number of factors, including knowledge. And we show that the ways in which knowledge was created and affected industrial organisation changed considerably between the two periods (Section 4). In order to understand these changes in the ILC we present a study of the mechanisms of knowledge generation and utilisation focusing on two knowledge intensive sectors: telecommunications and biotechnologies (Section 5). Section 6 concludes on how ILC should be modified in the case of knowledge intensive sectors.

2. The industry life cycle and the changing knowledge environment

The idea that the dynamics of industrial sectors could display regular patterns of development, including both discontinuities and cyclical behaviour, emerged in the 1970s with such concepts as dominant designs (Abernathy and Utterback, 1975), technological regimes (Nelson and Winter, 1977), technological guideposts (Sahal, 1985), and technological paradigms (Dosi, 1982). However, it was not until a series of empirical and analytical studies (see Klepper, 1996, 1997; Jovanovic and McDonald, 1994; Utterback and Suarez, 1993) in the 1990s that the concept of ILC took on a more accurate meaning. While these authors disagreed on the likely causes of the ILC, an empirical regularity can be found in all their studies. The number of firms initially increased, reached a maximum, and then declined to the point where a relatively concentrated industrial structure was attained. The situation where the number of firms had reached its maximum and started declining was termed shakeout. Other regularities were found, such as the balance of product and process innovation, often but not always shifting from the former to the latter as the ILC moved from early to more mature stages. These other regularities are well established but of less general significance than the time path of the number of firms.

In recent studies of industrial dynamics a number of phenomena have emerged not previously identified in ILC research. Initially, virtually all the ILC studies were based on sectors that had developed between the beginning of the 20th century and the 1970s. All these sectors were created from nothing. Following a Schumpeterian logic we would expect this. According to Schumpeter (1935), you can 'add as many mail coaches as you like, you will never get a railroad by so doing'. In other words, we could not expect a new technology (trains) to be produced by the same firms that produced the old technology (mail coaches). Creative destruction worked to eliminate the old firms to make way for the new ones. However, from the late 1970s a number of important industry sectors were profoundly restructured as a result of certain radical innovations which substantially changed the type of knowledge used by these sectors. The dynamics of some important new industrial sectors created since the 1980s seem to be characterised by three – closely related – phenomena not previously observed in ILCs: the survival of incumbent firms, the emergence of new firms, and the development of innovation networks.

2.1. The survival of incumbent firms

The survival of incumbent firms belonging to pre-existing sectors was observed in spite of radical innovations which might have been expected to lead to the emergence of new sectors and new firms. Within these sectors incumbent firms, typically large diversified firms (LDFs), survived the emergence of knowledge sufficiently new to be qualified as belonging to a different paradigm. In other words it would seem that the producers of mail coaches were able to produce trains. However, the power structure among these surviving firms did not remain unchanged: some incumbent LDFs were able to take greater advantage than others of the emerging forms of knowledge. Thus, the ranking of incumbent LDFs changed as a result of this knowledge transition.

2.2. The emergence of new firms

In knowledge intensive sectors, the emergence of new firms, high technology start ups, has played a crucial role in the development of the knowledge bases of relevant sectors. In most cases, the adaptation of incumbent LDFs to the new paradigm did not occur through their internal efforts and resources. Of even greater significance in this adaptation process was the emergence of NTFs as a new type of industry actor. The main function of NTFs was to interact closely with both public research institutes (PRIs) and with incumbent LDFs to allow the development and utilisation of new types of knowledge in the relevant sectors. In some senses NTFs behaved as intermediaries between PRIs and LDFs.

2.3. The development of innovation networks

The co-existence of LDFs and NTFs occurred through the formation of INs and alliances generally including incumbent LDFs, NTFs and PRIs. The INs which developed with increasing frequency after the late 1970s are substantially different from any previous form of inter-firm collaboration. The main purpose of INs today is the creation and diffusion of new knowledge, a function that in the past firms had always tried to carry out internally and to closely control. This co-existence of NTFs and of LDFs within INs can in fact be seen as a combination of the entrepreneurial and the managerial routes to innovation, or as Schumpeter Mark 1 and Mark 2 (Freeman, 1982; Andersen, 1994; Malerba and Orsenigo, 1996). Whereas Schumpeter Mark 1 is based on a heroic vision of the entrepreneur, an innovator who brings along economic change and generates new knowledge on his own, Schumpeter Mark 2 takes into account the role of large firms, of structured organisations with institutionalised research and development departments. Within modern INs, thus, both LDFs and NTFs play a role: NTFs provide a technical knowledge, while LDFs provide organisational and market knowledge.

3. Historical trends

There are at least three types of historical trends in which knowledge has affected industrial dynamics, leading to the emergence of LDFs, their expansion with the institutionalisation of industrial R&D, and finally their survival and co-existence with NTFs within INs.

3.1. The long term trend in the development of the capitalist system

LDFs emerged mainly towards the end of the 19th century. Prior to this time, large firms were the exception. This transition corresponds to the *emergence of the visible hand*, using a terminology introduced by Alfred Chandler (1962, 1977), the most influential interpreter of the growth of the corporate economy. The first market in which these developments took place on a large scale was the USA. As a consequence of several new technologies, such as transport, telegraphy and refrigeration, some firms escaped their local origins and established branches in various parts of the USA. This change of strategy allowed firms to take advantage of scale economies and increasing throughput. This strategy of delocalisation was accompanied by a new organisational structure, consisting of internal specialisation of functions. This gave rise to large, hierarchically organised firms composed of many units, each administered by salaried managers (Chandler, 1962, 1977). In this process firms moved to a higher degree of vertical integration by internalising functions previously carried out by external independent producers. Research and development (R&D) was one of the functions that was internalised within this U form. As markets for homogeneous products were gradually superseded by markets for differentiated products the predominant firm structure changed to the multidivisional, or M form. However, after the 1970s a trend towards vertical disintegration was observed. Richard Langlois (2003) called this trend the *vanishing hand*. It is exemplified by the growing tendency of firms to contract out a number of the functions that they had previously managed internally.

3.2. A secular trend towards growing knowledge intensity in capitalist economies

The trend towards the so-called knowledge based economy, is by no means new. Its foundations were laid during the 19th century with the creation of the Humboldt university system in Germany and the institutionalisation of industrial R&D in both Germany and the USA (Murmann, 2003; Mokyr, 2002). This trend accelerated considerably after the Second World War, when, following a basic Schumpeterian intuition, R&D became a routinised practice for most industrial firms (Baumol, 2002). While knowledge had always been used in virtually all types of human enterprise, with the introduction of the Humboldt university system and with the institutionalisation of industrial R&D, knowledge began to be created in specialist institutions. In other words, while previously knowledge creation had been a by product of other activities, from the second half of the 19th century it began to be created in knowledge producing or using institutions. The creation of institutions specialised in knowledge production and use was a truly revolutionary innovation (Freeman and Soete, 1997).

3.3. The emergence of a radically new type of knowledge, corresponding to a new paradigm

Industrial developments arising from advances in specific domains, such as molecular biology in the pharmaceutical and agrochemical sectors and information and communication technology (ICT) in the telecommunications sector, provided the discontinuities and knowledge shocks required for the launch of a new paradigm. As will be discussed later, incumbent LDFs were faced with the need to learn a new technology which had little in common with their current knowledge base. Internal learning processes could be speeded up through the collaboration with start ups that had the necessary competencies to understand and develop the new knowledge. The emergence of new technological paradigms had occurred before without causing a similar transition in industrial organization. Examples of such technological paradigms are polymer science in the industry of synthetic materials starting from the 1920s, and transistors, leading to modern electronics and ICT, starting from the 1950s. The transition to these paradigms was carried out within the research laboratories of LDFs. What we observe today as a new phenomenon is the emergence of knowledge discontinuities taking the form of an increasing rate of creation and diversity of new knowledge, and introducing important changes in industrial dynamics. Especially, the profile of evolution of knowledge intensive industries tends to be distinct from traditional ILC, since knowledge discontinuities affect LDFs without challenging their survival, stimulates the creation of performant, but yet not dominant NTFs, and finally sustains the development of INs (including both LDFs and NTFs) as a stable form of industrial organisation.

4. Knowledge and industry life cycle in the visible and vanishing hands

In this section we discuss how ILC has changed over time. In particular, we focus on the transition from separate knowledge bases in vertically integrated firms during the visible hand period, to the overlap of knowledge bases within INs during the vanishing hand.

4.1. ILC and the visible hand: vertical integration and the coordination of distinct knowledge bases

As was previously pointed out, several factors contributed to the creation of U and M form firms. These factors included a number of technologies, such as trains, telegraph and refrigeration, which allowed firms to coordinate their activities over long distances and to preserve the quality of some types of merchandise during their transport. This allowed firms to take advantage of scale economies and exploit the large geographical markets which, while potentially existing before could not have been exploited due to transport and coordination problems. Clearly, some type of knowledge was involved in the emergence of large, vertically integrated, hierarchical organisations. For example, organisational knowledge for administering the emerging large corporations was of vital importance. Chandler (1977) shows how the railways in the USA were not only of importance in providing an adequate transport technology but also because they were a test bed for the creation of managerial knowledge. Yet, this and many other types of knowledge required to administer a large corporation were mostly acquired through learning by doing. No management schools existed to systematise the required organisational knowledge. The knowledge that was produced in specialised institutions only started to affect the creation of the U form firms when the first industrial R&D laboratories were created. Studies of these early R&D laboratories (Hounshell and Smith 1988; Reich, 2002) show how the decision to create internal R&D laboratories rather than relying on independent inventors was largely due to appropriability problems: knowledge from independent inventors would have been equally available to competitors. In the early 20th century the firms carrying out internal R&D were few. Although industrial R&D has always tended to be more applied than university-based, it nevertheless belonged to the new breed of knowledge created in specialised institutions. Clearly, industrial R&D could be used to gain competitive advantage by creating innovations which would give the firm a temporary monopoly. Here we can observe that although the internalisation of industrial R&D corresponded with the trend towards vertical integration, which shaped the emerging large corporations, R&D was at the same time a completely new function, corresponding to a new mode of learning. Thus, knowledge had an impact on the structure of the emerging large, vertically integrated, hierarchical corporations, although it acted in conjunction with other factors (transport technologies, scale economies, etc.) and through very different mechanisms with respect to the present.

4.2. ILC in the transition phase: vertical desintegration and the progressive overlap of knowledge bases

A number of changes in the mechanisms of knowledge generation and utilisation occurred during the 20th century. To start with, the rate of creation of new knowledge has increased considerably. Equally importantly, the average delay between the creation of a new idea and its industrial utilisation has reduced from 32.75 years between 1887-1906 to 3.4 years between 1967-1986 (Agarwal and Gort, 2001; Baumol 2002). This faster utilisation of scientific and technological knowledge for industrial use is part of the recent changes in the creation and utilisation of knowledge. These changes have been described as the transition from Mode 1 to Mode 2 in knowledge generation and utilisation (Gibbons *et al.*, 1994).

Mode 1 corresponded with the existence of a clear cut distinction between fundamental and applied research, in which the two types of research were carried out in different institutions (universities or basic research institutes, and industrial firms respectively), at different times, and were evaluated by different means (the peer review system and the market respectively). Furthermore, fundamental research was generally carried out in advance of industrial applications. This neat chronological and institutional separation of fundamental and applied research disappeared to a considerable extent in the transition to Mode 2. Institutional boundaries became fuzzier, as universities began to do more applied research and industrial firms undertook more fundamental research. Although the distinct goals of the two institutions did not disappear, there was an increasing overlap of their knowledge bases and of their institutional boundaries. The increased speed of industrial utilisation of new ideas referred to above can be considered both as a cause and as an effect of the transition from Mode 1 to Mode 2. Another important change that took place during the same period is the growing use of spillovers by firms, a phenomenon that sometimes takes the form of the voluntary dissemination of proprietary knowledge (Baumol, 2002). Spillovers have been recognised as contributing to the ability of economic systems to create long term economic growth by providing increasing returns to adoption.

4.3. ILC in the vanishing hand: knowledge base within INs

The formation of a new type of inter-firm alliances, variously referred to but which we call here INs, was first observed in the late 1970s. These alliances differed from previous ones in that their main objective was the creation of new knowledge. Previously firms had collaborated in various ways, such as contracting out the production of spare parts, developing joint ventures, etc. Knowledge was involved in all these types of collaborations, but their main objective was not the creation of new knowledge. For example, in joint ventures the most advanced firms would license a technology they had already used in more advanced markets to firms in less advanced markets. In other words, joint ventures consisted of the exploitation of already existing and maturing types of knowledge, not the creation of new knowledge. If we recall that the motivation to internalise R&D in large corporations was to avoid the risk that this knowledge was made available to competitors, we can see that the joint creation of new knowledge by inter-firm collaboration would have been very unlikely prior to the 1970s. In fact, the initial reaction of many economists to INs was that they could not last. INs were considered a reaction to a shock that had been experienced by incumbent firms and sectors, to which in the short run they could not react in the usual ways. Thus, the existence of INs was considered to be temporary. Most economists forecast that INs would be replaced either by markets or by large, vertically integrated corporations, the only forms of industrial organisation considered stable at that time. The subsequent and continued growth in the numbers of INs proved them wrong. Even if they were eventually to disappear at some time in the future, INs had acquired their place amongst recognised forms of industrial organisation.

One might see the formation of INs as a form of vertical disintegration; however, the simple presence of firms supplying inputs to other firms that previously produced them internally can be interpreted in various ways. Two extreme cases can be envisaged:

(i) that both the external supplier and the purchasing firm have the capability to produce the required inputs and that the decision to contract out production is based on the cost advantage of using the external supplier. In this case, the knowledge bases of the two parties in terms of production capability are similar.

(ii) that large incumbent firms are faced with the need to acquire new knowledge to maintain their competitiveness. When the new knowledge is very different from the existing knowledge, the ability to create knowledge in the new field may be more difficult for incumbent firms than for start ups with competencies similar to those of the research institutions that created the new knowledge. The combination of a large incumbent firm and a start up will facilitate more speedy creation and exploitation of new knowledge than the lone internal efforts of an isolated LDF. In this case the knowledge bases of the two parties are asymmetrical, with start ups having the new technological knowledge and the LDFs providing complementary assets and competencies.

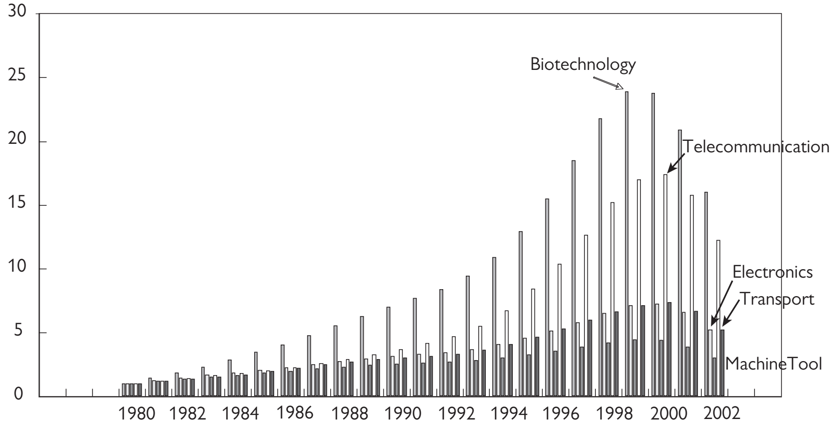
5. The case of telecommunications and biotechnology

Now that we have clarified how knowledge affects ILC, we can learn more on knowledge intensive industry life cycles on the basis of two specific cases: biotechnologies and telecommunications. In this section we will describe the results of our recent research on the dynamics of knowledge in biotechnology and telecommunications. INs play a very large role in these two sectors, which are amongst the most knowledge intensive in the economy. Thus, they are appropriate to display the relationship between changes in knowledge dynamics and in industrial organization. In the meantime, however, confirmation of the existence and validity of this relationship would certainly require a more comprehensive analysis including a larger sample of industrial sectors.

5.1. Knowledge dynamics

Both telecommunications and biotechnology can be considered as knowledge intensive sectors, since there has been a higher rate of knowledge production than in other sectors such as electronics, machine tools or transport (see Fig. 1), and a greater discontinuity in the process of

1. Index of the (5-year-)moving average of the number of patents with the base year 1980.



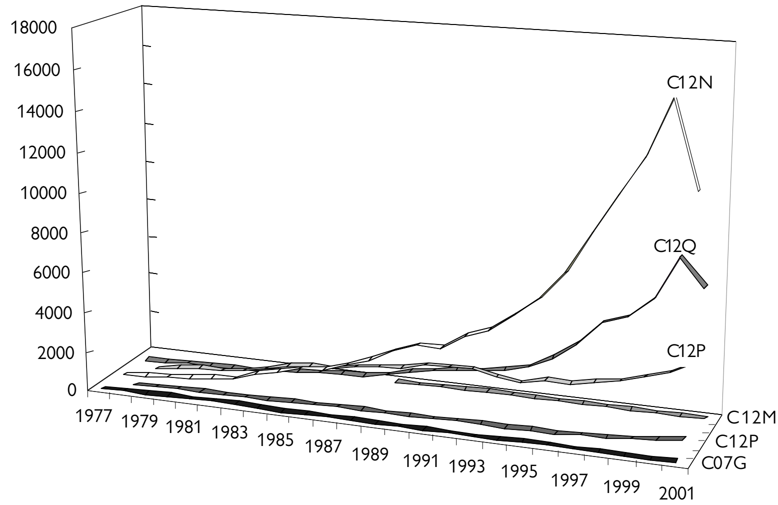
knowledge generation and utilisation. These sectors were thus faced with the emergence of a radically new type of knowledge, corresponding to a new paradigm.

5.1.1. Biotechnologies

Modern biotechnology, sometimes called third generation biotechnology, has its origins in the emergence of a new scientific discipline, molecular biology. Molecular biology was created in the 1930s in the USA to apply the methods of physics to biology (Goujon, 2001). Before the 1970s molecular biology had produced some spectacular discoveries, such as the DNA double helix, but no candidates for short term industrial applications. This did not occur until the 1970s when the discovery of recombinant DNA and monoclonal antibodies created expectations of short and medium term industrial applications. In principle, biotechnology could find applications in many industrial sectors: it was a pervasive (Freeman, 1982) or general purpose technology (GPT) (Breshnahan and Trajtenberg, 1995). Initially most applications were within the pharmaceutical industry, where most of the investment continues to be concentrated.

The emergence of new biotechnology represented both an opportunity and a problem for incumbent firms in the sectors where this new technology could be applied. The opportunity lies in the very wide range of potential applications; the problem is the great cognitive distance separating the new biotechnology from the knowledge base of firms in the relevant sectors. In spite of the potential attraction of biotechnology, incumbent LDFs had very low absorption capacity in relation to it. The opportunities were seized by entrepreneurs, often ex employees of PRIs, who founded

2. Evolution of patents in the biotechnology industry on the 4-digit level of the IPC.



the first NTFs (McKelvey, 1996). For all their knowledge proximity to the PRIs in which the new knowledge was created, NTFs did not manage to replace incumbent LDFs in the way Schumpeter had envisaged. NTFs did not have all the resources required to produce the final output. Thus, a situation of complementarity was created between NTFs, which were much faster learners of the new 'core' knowledge, and LDFs, which had the necessary complementary assets (Pyka and Saviotti, 2005).

This industry configuration and its consequent industrial dynamics depended crucially on the presence of a knowledge discontinuity. Biotechnology is one of the fields where the growth in the number of patents has been fastest. Its proximity to fundamental research clearly qualifies it as a knowledge intensive field. Radical change in this case was represented by the differential growth rates of new technological classes within the patents applied for by firms in the relevant sectors. The composition of the knowledge base of the firms changed as a consequence, with a large domination of some technological classes (C12N, micro-organisms or enzymes; C12Q, measuring and testing processes; C12P, fermentation), and the abandonment or stagnation of others (C12M, apparatus for enzymology and microbiology) (Fig. 2).

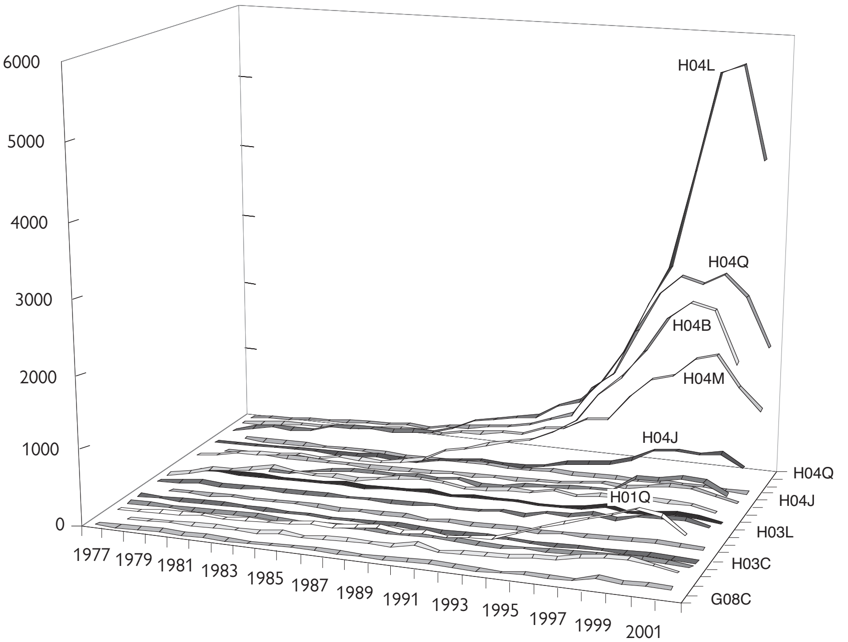
5.1.2. Telecommunications

In the telecommunications industry a similar process of radical change took place and the KBs of firms changed by incorporation of new technological classes and elimination of old ones.

For a long time, the circuit-switched paradigm had shaped thinking and learning about how to achieve improvements. This paradigm was developed within the central research laboratories of the monopoly telecommunications operators (the telcos), the essential technology providers at that time. In fact, within the circuit-switched paradigm incumbent telcos controlled the operation of the infrastructure and the provision of simple and standardised telecoms applications (essentially voice calls, fax, i.e. POTS - Plain Old Telecoms Services). Knowledge accumulation was internal to the national companies, but was also based on cooperative competition that existed between national systems to be the first to introduce the next generation of technologies and services. One example is given by the races that took place to develop the next generation of switches, races that were nonetheless punctuated by the formal and informal sharing of information through institutions such as regular international switching conferences, which brought together the world's best. During that period the dominant strategy was exploration of a large range of new fields and applications, with the aim of preserving national excellence by preventing competition from abroad. In terms of patents, the telecommunications industry was classified in section H – Electricity, with some incursions into section G – Physics. Many of the technological classes and sub-classes in section G are more 'fundamental research' oriented than section H (which is more 'applied'). At first, telecommunications companies (and their associated R&D laboratories) accumulated competences in basic electrical instruments (HO1) to elaborate the infrastructure over which the telecommunications services (the signal at this stage) would be provided. This basic knowledge had to be combined with patents in the domain of selection (HO4Q) and transmission (HO4B) of the signal.

The emergence of packet-switching technologies alongside TCP/IP protocol, URL and the World Wide Web generalisations, drastically modified the way in which knowledge was created and combined. NTFs, such as new entrants in network operation, Internet Access Providers (IAPs), Internet Service Providers (ISPs), equipment suppliers specialised in data transfer, security and navigation on the Internet, played a key role in determining the way in which knowledge could be produced and used. New Internet-related technologies produced a technical separation between the network and the potential services offered, implying that these NTFs could simply lease the infrastructure from network operators, or develop on it some points of presence (PoP). An open set of applications (PANS - Pretty Amazing New Services) emerged largely in this period. With these changes, the coordination of different bits of knowledge, held by different actors, required a more systematic effort, often supported by INs (Krafft, 2004). During this period, the accumulated knowledge was related to cable technology (HO1B) – for fixed telephony and Internet, but also to aerials and semiconductors (HO1L and HO1Q) for mobile telephony and Internet. While selection is rather generic in the early

3. Evolution of patents in the telecommunications industry on the 4-digit level of the IPC.



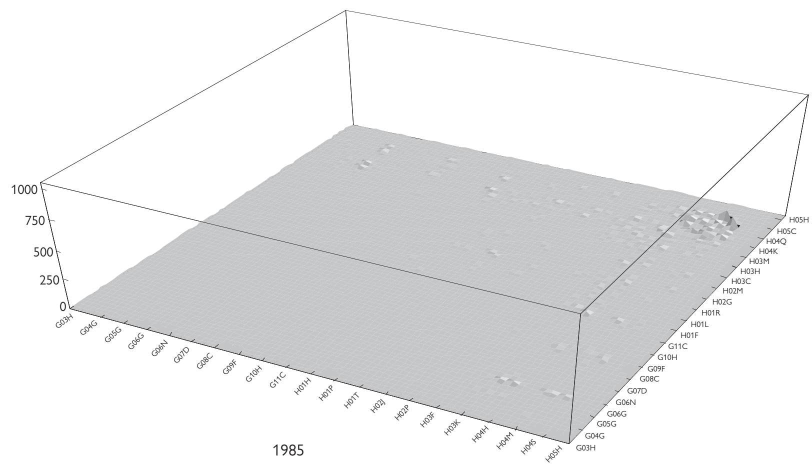
stages of development of the telecommunications industry, transmission becomes more specific over time, towards digital signals (HO4L), multiplex signals (HO4J) and pictorial signals (HO4N) for new applications in Internet and mobile. Companies that specialise in Internet and mobile activities generally require additional knowledge in physics: in optics (GO2B) for the development of optical fibres in the domain of fixed broadband Internet, and in electrical digital data processing (GO6F) for high speed Internet either fixed or mobile.

Fig. 3 exhibits the recent trend in the evolution of patents. We can immediately see that there is a striking difference in the rates of growth of different classes, with two or three classes accounting for most of the growth and the other classes contributing very little. HO4L leads, closely followed by HO4Q, HO4B, and HO4M.

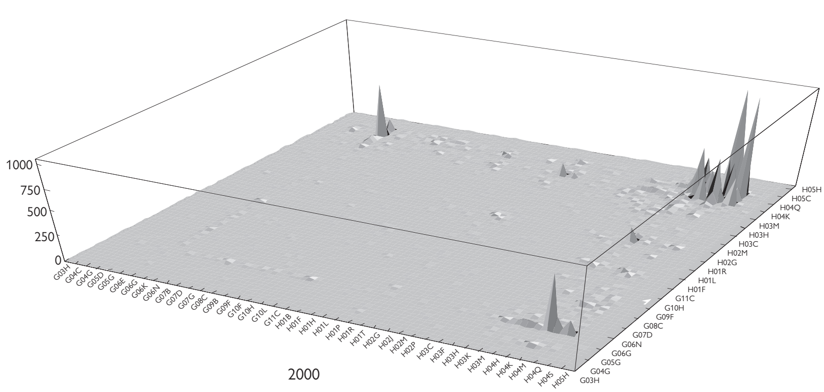
5.1.3. Knowledge discontinuities and search strategies

A matrix of co-occurrence of the technological classes in the patents of biotechnology firms can be constructed by placing the same technological classes ($T_1 - T_n$) on both axes and writing the frequency of co-occurrence of the classes T_i and T_j in the cell corresponding to the intersection of row i and column j. We can obtain a graphic representation of the state of this matrix at different times by plotting the frequency of co-occurrence on a third, vertical axis. By comparing the states of the co-occurrence matrix we can map the evolution of the knowledge used by firms in a given field/ sector (Grebel *et al.*, 2005). As we can see from Figs 4-7, search strategies for the new knowledge evolve from *random search* immediately after the discontinuity, when firms can perceive the opportunities inherent in the new knowledge, but have not yet identified promising directions of development, to a later, more *organised search*, when most firms can identify within the new knowledge the more promising trajectories. Such a time path is clearly related to the discontinuity represented by the new knowledge that firms need to internalise.

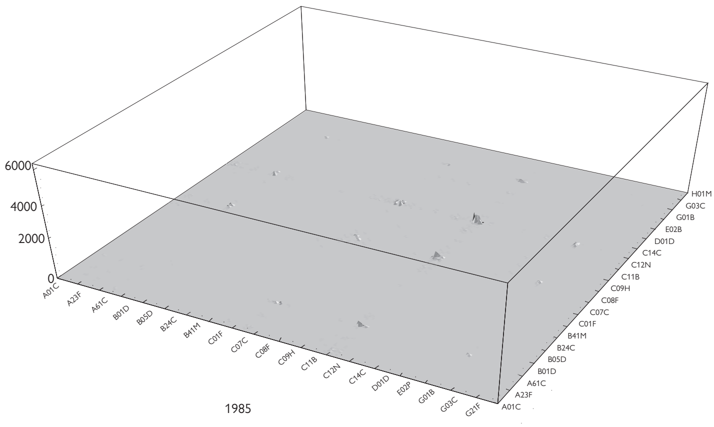
4. Knowledge in Telecommunications during the random screening period: evidence from patenting activity



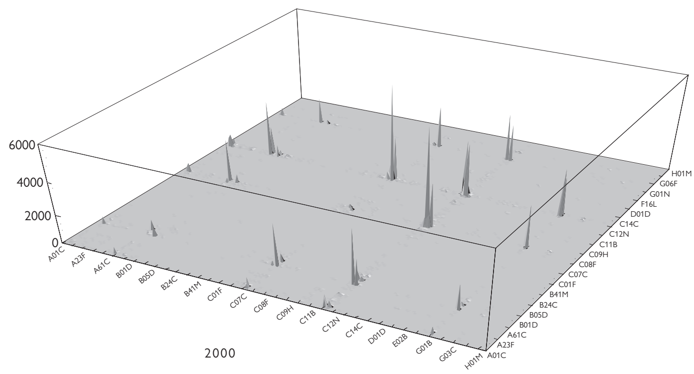
5. Knowledge in Telecommunications during the organized screening period: evidence from patenting activity



6. Knowledge in Biotechnology during the random screening period: evidence from patenting activity



7. Knowledge in Biotechnology during the organized screening period: evidence from patenting activity



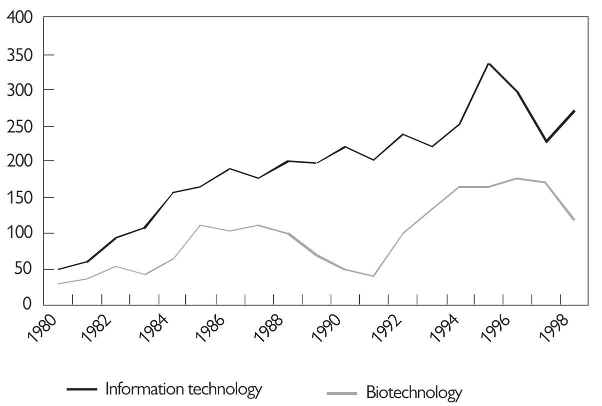
Within the highly uncertain period immediately following the emergence of the new technology the search is random and aimed at learning in all possible directions, stressing differentiation. As the new knowledge landscape is explored more, some directions of development emerge as being the most promising. Search becomes more structured around a restricted number of knowledge types and improving the integration of these types of knowledge increases in importance. The shock of novelty produces uncertainty and induces a random search while subsequent learning processes select some subsets of the new knowledge space and structure the search processes around them. The existence of a random search period is an indication that a radical change in knowledge is occurring. The exploration of a completely new part of the knowledge space can be expected to proceed initially without clearly established rules or well defined trajectories. Subsequent research can be expected to follow the rules and trajectories which emerged during the random search phase. This result is reinforced by that of Nesta and Saviotti (2005), who found that, while both the differentiation and the coherence of the knowledge bases of pharmaceutical firms were important determinants of their technological performance, the latter became progressively more important going from the 1980s to the 1990s as the new biotechnology started maturing. Differentiation predominated in the random search phase and coherence became more important moving towards the organised search period.

5.2. The co-existence of LDFs, NTFs within INs

Although there are INs in many sectors, their frequency is particularly high in information technology (IT) and in biotechnology (Hagedoorn, 1993, 1995), which are at the basis of several important industrial sectors and which are usually considered high technology (Fig. 8).

Very radical changes in the knowledge bases of both ICTs and biotechnology took place in the period 1970-1990. IT developed very vigorously after the Second World War. Its convergence with telecommunications substantially enlarged their respective markets and transformed telecommunications from a state monopoly to an extremely competitive sector which could supply consumers with a rapidly improving supply of services. Since the late 1970s biotechnology has become the new knowledge base of pharmaceutical firms and is profoundly affecting agrochemical, food, chemical and environment related firms. The

8. Evolution of international strategic alliances in information technology and in biotechnology.



emergence of biotechnology is the result of the emergence of a new discipline, molecular biology, established in the 1930s to apply physics methods to biology. In both these cases the changes outside the immediate firms and sectors were radical, and can be considered as the transition to a new technological paradigm (Dosi, 1982). This discontinuity in knowledge had profound implications for the strategy of incumbent LDFs and led to their co-existence with NTFs within INs both in biotechnologies and telecommunications.

5.2.1. Biotechnologies

Picture, for instance, the situation of a pharmaceutical firm in 1975, when the discoveries of recombinant DNA and monoclonal antibodies (Goujon, 2001) had just opened the door to industrial applications of biotechnology. An incumbent LDF needed to decide whether, how and when to commit itself to the new biotechnology. It was not an easy commitment, since the knowledge base of pharmaceutical firms had previously been constituted mainly of organic chemistry. In other words, incumbent pharmaceutical firms had a large cognitive distance (Nooteboom, 2000), or equivalently, a low absorption capacity (Cohen and Levinthal, 1989, 1990), with respect to the new biotechnology. The change in strategy that incumbent firms were facing was drastic, involving the replacement of a very large share of their existing research personnel by researchers with new and very different competencies. Such a process could only be envisaged as occurring over a long period, with a longer timescale for larger firms. The creation of absorptive capacity in incumbent LDFs could also be seen as taking a long time. However, the emergence of a new type of industrial actor, the NTFs, which in the case of biotechnology were known as dedicated biotechnology firms, provided incumbent LDFs with an alternative strategy. NTFs, particularly in the case of biotechnology, were often founded by scientific entrepreneurs who had previously worked in PRIs. Their knowledge proximity to the new biotechnology and the small size of the firms they founded allowed them to be very fast learners of the new biotechnology. However, NTFs in general did not have the complementary assets (Teece, 1986) required to transform knowledge into final outputs. A relationship of complementarity was created between NTFs, which had the new scientific and technological knowledge, and LDFs, which had the complementary assets (finance, marketing etc.). It soon became clear that the collaboration between LDFs and NTFs could create new pharmaceutical products faster than internal development of either LDFs or NTFs (Pyka and Saviotti, 2005). In these circumstances INs were a better form of industrial organisation than either the market or the large corporation. To analyse the problem in a slightly different way, one could say in the external environment of the late 1970s neither Schumpeterian entrepreneurs nor large corporations could alone provide the best industrial development route for a new technology.

This was the result of a discontinuity represented by the emergence of new paradigms and by the increasing rate of creation of new knowledge.

5.2.2. Telecommunications

A similar process occurred in the telecommunications industry. The emergence of packet-switching technologies on which the Internet is based, generated a new set of applications for LDFs in the telecommunications equipment and telecommunications carrier industry. However, the incumbent firms were generally reluctant to develop these applications on their own (Fransman, 2003). Their knowledge base was essentially related to the traditional circuit-switching technologies, which had been developed in their own central research laboratories. These laboratories, which in many cases, and especially in Europe, were also PRIs (see for example CNET in France and CSELT in Italy) were at that time the essential technology providers. Thus, one could also say that LDFs, both incumbent telcos and equipment suppliers, had a large cognitive distance with respect to Internet technologies, or alternatively that their absorption capacity for IT was low. Applications for the Internet, including all the software needed to transfer data, browse and secure networks, were generally developed by NTFs. These NTFs, often run by former PRI or incumbent company researchers, motivated by the profit opportunities offered by the emerging Internet market, quickly developed the necessary knowledge and related competencies. However, as traffic increased and the commercial applications of the Internet became a global phenomenon, NTFs needed the complementary assets developed by LDFs. For a while this complementary relationship occurred predominantly by means of mergers and acquisitions between LDFs and NTFs. In the exuberant financial environment of the 1990s, it also took the form of INs. Although their frequency was temporarily reduced by the 2000 financial bubble, INs as a form of industrial organisation globally survived the financial crash (Krafft and Ravix, 2005; Krafft, 2004; Krafft, 2006).

5.2.3. Summing up

The main hypothesis formulated in this paper is that the change in industrial organization which gave rise to the INs during the 1980s was partly due to changes in knowledge dynamics. These changes could be due to two causes:

(i) Changes in technological paradigms, introducing radically new knowledge

(ii) A growing rate of creation of new knowledge

This does not mean that knowledge had not been affecting industrial organization before. As it was previously pointed out, even the institutionalization of industrial R&D in the multifunctional and in the multidivisional corporations was due to the need to preserve appropriability, a consequence of knowledge being a partly public good.

These changed circumstances, which were described above as being part of the transition from Mode 1 to Mode 2 of knowledge creation and utilisation, gave rise to a new form of industrial organisation, which was created by the collaboration of NTFs, acting as Schumpeterian entrepreneurs, and of incumbent LDFs. The latter supplied a wide range of knowledge and of complementary assets and were capable of coordinating them, but they were less able than NTFs to carry out search processes within the new knowledge. As a result of this collaboration LDFs increased their absorptive capacity (Grabowski and Vernon, 1994) but could not replace NTFs since new fields of knowledge keep emerging and create renewed scope for NTFs (Pyka and Saviotti, 2005). Thus, INs became a stable form of industrial organisation. However, it is not clear whether they are a phenomenon apart, or a component of the broader trends in capitalist development described above.

It could be said that the emergence of NTFs and INs corresponds with the trend towards vertical disintegration described during the vanishing hand (Langlois, 2003). However, INs need to be distinguished clearly from the externalisation of functions that firms have the capabilities to carry out, but that they find more cost effective to outsource. For example, firms such as Solextron and Flextronics specialise in contract work assembling electronic systems of all kinds, while DSM, for instance, produces drugs to order (for further examples see Langlois, 2003). While in the case of INs NTFs are much closer to the technological frontier than LDFs, in a cost based externalisation of functions the relevant knowledge is largely and symmetrically shared by the participating firms. Thus, two situations can appear very similar when judged by the frequency of externalisation of functions and by the numerical ratios of large and small firms. At the extreme of INs the distribution of knowledge is highly asymmetrical, with NTFs being much closer to the technological frontier and with LDFs owing their survival to the ownership of complementary assets and to their coordination capabilities. At the other extreme of a purely cost based vertical disintegration the distribution of knowledge amongst firms can be very symmetrical, although one firm can still play a much greater coordinating role than the other. If we take into account this potential difference underlying the trend towards the vanishing hand, we can consider INs as part of such a long term trend that deserves a modified ILC model.

6. Summary and conclusions

In this paper we discussed the survival of LDFs, emergence of NTFs and co-existence within INs as very significant phenomena affecting the ILC. We have tried to position the discussion in the context of long term developments in the capitalist economic system. Our conclusions are as follows.

Starting from the end of the 19th century, long term patterns of capitalist development led to the formation of large, vertically integrated hierarchical organisations, a trend which Chandler calls the *visible hand,* and one that lasted until the 1970s. After this time a reversal of this trend started to emerge, in which firms began to externalise a growing proportion of their activities. Although large, vertically integrated hierarchical organisations have not disappeared, the new trend is clearly observable and was referred to by Langlois as the *vanishing hand*. In this paper we maintain that the ILCs reported in the literature, in the period between the end of the 19th century and the 1970s, were specific to the period of the visible hand. Cyclical phenomena have not disappeared from the evolution of industries, but they no longer result from the same mechanisms.

In this study we concentrated on two knowledge intensive sectors, telecommunications and biotechnology, for the period 1970s-2000. In both cases we found that the emergence of a radically new type of knowledge leads to an initial period of *random search*, during which firms simply try to position themselves in the new knowledge space. The period of random search is followed by another period of more *organised search*, when firms start to focus on a selected subset of the new knowledge and begin to integrate this new knowledge in their knowledge bases.

This general knowledge dynamics creates conditions in which INs are superior to the internal efforts of isolated firms. As long as there is a high rate of creation of novelty in an economy we can expect INs to continue to be a stable form of industrial organisation. As a consequence INs can now be considered a basic component of the ILC.

The above considerations have to be qualified by saying that INs are not the only form of vertical disintegration that began to occur during the vanishing hand period. Another, numerically similar, although different in content, form of vertical disintegration is that in which functions that a firm is fully capable of are externalised for cost reasons. In this case the distribution of knowledge amongst firms is far more symmetrical than in INs where considerable knowledge asymmetry is the main factor leading to the externalisation of R&D and of search processes.

This obviously points towards the need for a modified model of the ILC to take account of the different industrial dynamics that started taking place from the beginning of the vanishing hand period, and in particular of the role that knowledge can play in new forms of industrial organization.

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