EVIDENCES ON INTER-FIRM R&D PARTNERSHIPS IN THREE HIGH-TECH INDUSTRIES

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Abstract

This paper describes inter-firm partnerships in three major high-tech industries over the 1985-2005 period. We found that the architecture of the respective networks had evolved toward a 'small world' in the early 1990s. We also found that the number of alliances collapsed in the late 1990s. This result roughly follows the number of patents granted in the respective industries and is correlated to an increase in market concentration, and to some extent to the rising number of mergers and acquisitions.

JEL Classification Numbers: L24, L6, O31

Keywords: Innovation, R&D Partnerships, High-Tech Industries, Network Architecture

1 Introduction

This paper examines inter-firm partnerships at sectoral level in three major high-technology industries over the 1985-2005 period. We opted for research and development (R&D) cooperation agreements, namely the contractual arrangements by which firms or academic institutions share and pool resources and coordinate their R&D activities. As these non-equity forms of collaboration are flexible and limited in their horizon, they should be distinguished from other forms of cooperation agreements like research joint ventures. We used SDC Platinum, one of the few databases with worldwide coverage that encompasses R&D partnerships in several industries, at both domestic and cross-borders levels. This database is continuously updated and therefore allows for the extraction of fresh data.

Our study focuses on the pharmaceutical, the semiconductor and the communications equipment industries. It exhibits four salient points: first, the number of R&D alliances stopped increasing in the late 1990s, and even started to decrease sharply after 2000. Second, during the most favorable period, *i.e.* 1989-1994, the architecture of the three sectoral alliance networks evolved toward a 'small world' layout. Third, the decline in alliance formation is concurrent with the collapse in the number of patents granted in the respective industries. Last, the recent changes in market structure characterized by both an evolution towards more concentrated markets and a rise in mergers and acquisitions (M&A) operations, shed light on the economic forces driving the drop in the number of partnerships after the year 2000. In this respect, the study bears out the Schumpeterian view that the dynamics of innovation affects the shaping of markets to a large extent. Likewise, it stands out that the use of R&D cooperative agreements as a way to breed innovation in high-tech industries is sensitive to the nature and the potential of future innovation developments.

This study complements previous papers on the subject. Among others, Hagedoorn (2002) provided evidence of the rise in the number of contractual R&D partnerships in high-tech industries[1] from the mid-1970s to 2000. Later, Hagedoorn and Roijakkers (2006) confirmed the increasing number of alliances in the bio-pharmaceutical industry during the same period. With reference to these two papers, the review of our data (updated to 2005 included) discloses a collapse in

[1]Inter-firm partnerships have been particularly drawn to industries like information and communication technologies (Hagedoorn and Schakenraad [1992]), semiconductor [Rowley *et al.* [2000], pharmaceutical (Mitchell and Singh [1992]), automobile (Hennart [1991]; Osborn and Baughn [1990]), biotechnology (Shan *et al.* [1994]; Walker *et al.* [1997]).

the number of R&D partnerships after 2000. It would certainly be worth considering additional studies to establish whether this drift is nothing but an ephemeral anomaly. Furthermore, Gay and Dousset (2005) make it clear that the evolving alliance network has given form to a 'small world'. Our findings are consistent with this last result. The authors also display a positive correlation between the number of alliances and the number of products already in the pipeline. Again, we confirmed the point for our three industries by correlating the number of alliances with the number of intra-industry patents. Interestingly, the latest theoretical literature on industrial organization supports these results (Goyal and Moraga [2001], Goyal and Joshi [2003]).

The paper proceeds as follows. The next section is a reminder of some of the technological breakthroughs, changing environment and path development in the three industries. Section 3 tackles the dynamics of R&D networks in these sectors. Section 4 discusses the main results, and integrates the data on patents, market concentration as well as details on M&As. The last section concludes and advances suggestions for future research in this area. Appendix A describes the contents of our databases and appendix B and C provide the related tables and figures.

2 A short perspective on the three industries

The three sectors under scrutiny have been propelled by steady innovation from the outset. Yet, several differences lie behind the features common to the innovation process and path development and are therefore worth considering.

The semiconductor is fairly recent compared to the two other sectors but it is a crucial component of the all-out information industry and the pervasiveness of the 'digital age'. It emerged from a few radical advances in innovation which were highly localized: in the United States, especially in the 'Silicon Valley'. Right from the start, the sector was characterized by small and very specialized companies but due to idiosyncratic features, the development of the new industry occurred in a specific ecosystem. For example, most of the numerous start-ups in the 'Bay area' were founded and staffed by former engineers and technicians from Harris Corporation. The development of the industry was driven by the law of Moore, which claims that memory capacity doubles every 18 months as a result of technological progress. This statement - which proved a self-fulfilling prophecy - was the sole driving force up to the mid-1980s when Japanese companies stepped in and started to exert mounting competitive pressure. The pressure impacted incumbent firms, mainly U.S. companies, among which many went bankrupt or had to give up their main business activity. Thus, Intel was constrained to start a new line of business - the designing and manufacturing of microprocessors - which eventually proved highly successful. Subsequently, Japanese companies became very active in forming R&D alliances. The industry's structure is currently based mainly on complex trans-national manufacturing networks in which Asia keeps reinforcing its role as a prominent manufacturing base that targets the emerging economies' sizeable markets.

The communications equipment industry (telecommunication thereafter) is a mature industry as it dates back to the infancy of the whole telecommunication industry. Up to the early 1980s and the deregulation of the U.S. telecommunication sector - *American Telephone & Telegraph*'s monopoly was repealed in 1984 and the company was then split up into autonomous entities - the telecommunication industry was in effect linked to the large telecom operators which enjoyed a 'natural monopoly' (*France Telecom* in France, *NTT* in Japan, among others). Somehow, the year 1984 was a symbolic hallmark for the whole telecommunication industry as it was followed by a surge in privatization and deregulation programmes worldwide. In the early 1990s the spreading development of the Internet required new skills and capabilities. Consequently, the main actors integrated downwards to capture new added-value sources. While firms - among which *Lucent* has proved the most aggressive - have decided since 2000 to concentrate on their core activities. 2001 marked a crucial year in the M&A partnership downward trend. Several reasons may help to explain the change: first, the saturation of numerous market segments - more especially the downturn in the mobile telephony infrastructure market; second, the bankruptcy of fledgling operators; third, the high pressure on pricing from telecom operators. Furthermore, several alliances with large partners failed due to conflict of interest and the difficulty to benefit from synergy forces. The innovation race has been less harsh than in previous industry, and yet, although some new companies have emerged like *Cisco Systems* of America and China's *Huawei*, the industry is still largely composed of traditional companies. As scale economies are becoming crucial for sustaining a competitive advantage, the industry is consolidating at fast pace on a worldwide basis through the merger route. It is also the best option to reach critical size. In addition, both sectors, semiconductors and telecoms, nurture strong linkages as the design and the use of integrated circuits are common elements in the production process of communications equipment.

The pharmaceutical industry is also a fully-grown industry, yet with some particular characteristics. First, it spends more on R&D, measured as a percentage of sales, than any other major industry. By way of illustration, *Pfizer* of America, the then global leader, allocated more than

14 percent of its turnover to R&D expenses in 2005. The situation specific to that industry can probably be explained by the longer and riskier research periods of time together with other numerous constraints (e.g. clinical tests, safety regulations, etc.) pharmaceutical firms must incur before new drugs can be delivered to the market. A second characteristic is that the innovation process involves numerous academic institutions alongside private companies. This feature has been compounded with the breakthroughs of biotechnology in the early 1990s, when the innovation process became largely science-driven. As the large pharmaceutical firms did not have the appropriate skills in that field, new firms emerged. However, since many companies lacked the large distribution channels, the marketing and manufacturing facilities, or simply the substantial financial resources needed, they merged with the large drug companies - primarily from developed countries - that were already engaged in a worldwide race to gain valuable market share. Because they were latecomers, Japanese companies actively participated in forming R&D alliances, and in the early 2000s Asian companies (mainly from India and China) were participating in cross-borders alliances so as to tap the R&D resources and skills they badly missed. After the 'golden era' of new drug discoveries in the 1980s onwards, pharmaceutical companies started suffering from a dearth of new products. In addition, pharmaceutical makers had to face another challenge as the patents' expiry dates for the largest-selling drugs were approaching fast. These factors can explain why drug makers from the U.S. and Europe went on an aggressive M&A spree in the early 2000s. The move was indeed congruent with the streamlining initiated in the mid-1990s by all the incumbent firms which had been forced to bear the increasingly growing cost of bringing innovative molecules to market.

3 Dynamics of R&D networks

We introduced data on the networks of R&D partnerships in three high-tech industries. We began with the numbering of alliances *per* year, and came up with some outstanding evidence, and then pursued the analysis by characterizing the evolution of the networks' architecture.

3.1 A rise until the mid-1990s and a collapse thereafter

Figure 1 presents the number of R&D partnerships *per* year for each industry over the 1985-2005 period. The figure clearly shows a rise in the number of contracts from 1985 to the mid-1990s, with an overall peak in 1994 followed by a dramatic decrease, which can be virtually equated with total collapse. The same characteristics apply for all three high-tech industries. In addition, contingent impacts on the shape of the curves can be drawn from the presence of the common 1994 peak.

- Insert figure 1 about here -

More precisely, the rise in the number of these contractual agreements took off in 1989 for the pharmaceutical industry, and during the following years for the two other sectors. Here, changes in the institutional setup in the United States and the European Union (Japan was already supporting cooperative agreements) is part of the explanation. The pharmaceutical sector displays the greatest number of alliances, far ahead of the semiconductor sector which is followed at some distance by the telecommunication sector. The increase in the number of alliances is irregular and idiosyncratic to each sector: pharmaceuticals witness three local peaks (in 1992, 1994 and 1997) 1994 being the most prominent; the semiconductor sector also displays three peaks (1991, 1994 and 1996).The telecommunication sector, for its part, shows two culminating points (1994 and 1997). A more recent upturn occurred in the pharmaceutical industry in 2005. It was mainly due to the Chinese and Indian investors' entry into the market.

3.2 Network characteristics and dynamics

Figures 2 to 10 display discrete-time images of the evolution of the three R&D networks. Interestingly, all three networks' evolution is fairly similar. The figures reveal the existence of a large network and a great component (more than 50 percent of the number of alliances) during the first two sub-periods of analysis. The networks are more dense and more complex in the second sub-period than in the first one. But in the last sub-period the number of R&D alliances drops dramatically. The R&D networks are only shaped by some isolated pairs (one-to-one ties) and a few isolated clusters.

- Insert figures 2 to 10 about here -

In this section, we examined the topological R&D network structure for the three high-tech industries. First, we explored the global structure of the three R&D networks; and second, we looked at the actual position of the top-ten actors of each industry within their respective R&D networks.

3.2.1 A 'small world' architecture

Recently, several structural properties of social networks have been updated, such as 'small world' properties and power-law degree distributions. 'Small world' is a class of network architecture which has been popularized in sociology by the so-called experience of Milgram (1967).

More recently, works conducted by physicists and mathematicians (Watts [1999], Watts and Strogatz [1998]) shed light on the topological properties of 'small worlds' (low average degree, high clustering index, and low average path length). The latest economic and managerial studies on network topology have shown that real world networks did not look either like the random network or the regular one[2]. The majority of these studies found that the network topology of the different sectors each possesses 'small world' properties. For example, in biotechnology (Powell *et al.* [1996]), in the semiconductor (Podolny *et al.* [1996]), in the German industry (Kogut and Walker [2001]), in strategic alliances (Verspagen and Duysters [2003]), in the venture capital industry (Baum *et al.* [2003]), in communication networks (Schintler *et al.* [2005]), in bio-pharmaceuticals (Gay and Dousset [2005]), in software (Lyer *et al.* [2006]), and in the world of economics (Goyal *et al.* [2006]). The networks endowed with these properties are widely thought to enhance creativity and influence the rate of diffusion as well as the efficiency of knowledge, competencies and resources exchange.

In each of the sectors we focused on, we proposed a dynamic investigation by splitting the 21-year period in three seven-year sub-periods (the choice of period length does not affect the results). First, we computed the number of firms that were partners in alliances as well as the average number of partners for each firm (table 1a). From this, we observed that the average number of partners is small in each sub-period, *i.e.* 2.58 at most for the whole network and 3.49 in the largest component. Second, we examined whether or not the biggest component matched the characteristics of a 'small world' configuration (table 1b).

- Insert tables 1a, 1b about here -

For that purpose, we compared the characteristics of networks of distinct size through a standard method that normalizes indexes by a corresponding index in an Erdos-Renyi stochastic network with the same average degree. More precisely, we gave to the number of firms in the largest component, the average of partners, the average clustering, in the Erdos-Renyi stochastic network with the same average degree, the ratio of clustering indexes, the average path length, the average path length in an Erdos-Renyi stochastic network with the same average degree, the ratio of average path length. A 'small world' network is typically a network with a large number of nodes, a small average degree, an average path length close to that of a random network with identical average degree (so the ratio of average path lengths should be close to

[2]For literature surveys on network topology see Albert and Barabási (2002), Watts (2003), and Newman (2003).

1) and a large clustering index with respect to that of a random network with identical average degree (so the ratio of clustering indexes should be much higher than 1). This is what we have obtained for the three industries. Clearly, the metaphor of 'small world' applies to large networks, *i.e.* the networks that emerged in the early 1990s (the semiconductor industry fits best the 'small world' architecture, with the pharmaceutical industry, and the telecommunication industry coming next). We concluded that during the 1990s the three sectors exhibited a 'small world' architecture.

3.2.2 The degree distribution

The degree of links, or degree centrality, refers to the number of partnerships a firm is involved in. A firm with a high score may be considered as central and consequently expected to play a non-negligible role in the network. It is indicative of the extent to which a firm has succeeded in developing a dominant position in the overall network of inter-firm partnerships. Tables 2a, 2b and 2c list the ten leading firms in R&D networks that show the highest degree (of alliances) in the three industries during each of the seven-year periods.

- Insert tables 2a, 2b and 2c about here -

In the semiconductor sector, among the top-ten firms in each sub-period, *Intel*, *Toshiba* and *Sony* are present as central actors in all time periods. One striking result is that there is a noteworthy change in the ranking in the three sub-periods. The same applies to the telecommunication sector, with the exception of *Motorola* and *Mitsubishi Electric* which are present in all time periods. In the pharmaceutical sector, even though *Eli Lilly*, *Bristol-Myers Squibb* and *Pfizer* are present in the three sub-periods of analysis, we can notice a significant turnover in the last sub-period. However, the pharmaceutical R&D network seems to be relatively more stable than the other two networks.

We then turned to the description of the entire degree distribution. In this respect, we looked at whether the degree distribution for each R&D network unfolds a power-law regime or not. A power-law distribution is a statistical distribution in which one variable is proportional to a power of the other. A power law[3] implies that the network has no 'typical' node, in the sense that

[3]When considering dynamical models of network formation, a power-law distribution may emphasize the presence of preferential attachment (Albert and Barabási [2002]). Considering a process of node arrival in which new nodes form a unique link with a current node means that the probability that the new node will be connected to a current node depends linearly on the degree of the latter node. Then, new nodes are more likely to link up with

a Gaussian distribution would have a mean node, and the distribution is scale-invariant (Albert and Barabási [1999]). Basically, a power-law distribution is more unequal than a Gaussian one, it typically contains few nodes with disproportionate degree. These highly connected nodes dominate the topology of the network by forming 'hubs'. Figures 11a, 11b and 11c exhibit the cumulative degree distribution for the three R&D networks.

- Insert figures 11a, 11b and 11c about here -

Further, a log-log representation is proposed in order to assess whether the distributions follow a power law (in which case one would obtain a linear relationship in log-log scale). The figures indicate an incomplete power-law relation, since the individual points of the degree distribution are not distributed along a straight line when plotted in log-log scale. This result is of importance, as it partly diverges from the 'physicists' explanation of the dynamic network formation la Barabási (2002)[4]. Given that our empirical cases lie in an intermediate position between a Gaussian and a power-law distribution, we concluded that R&D networks are not totally cannibalized by a few firms, in spite of the crucial role played by the main actors.

3.2.3 The betweenness centrality

The betweenness centrality is an instructive indicator of network position. Basically, it measures the extent to which a particular node lies on the shortest paths linking other nodes in the network, and consequently the extent to which a firm, landing on the shortest path between two other companies, has a potential for accessing and controlling information (Burt [1992]). Tables 3a, 3b, 3c present the top-ranking firms in terms of betweenness measures for the first two sub-periods (1985-1991 and 1992-1998) for each R&D network (the number of alliances being too low during the last sub-period to provide relevant betweenness indexes).

- Insert tables 3a, 3b and 3c about here -

The comparison with degree centrality does not show a noteworthy change in the magnitude of betweenness centrality for the three R&D networks. Let us illustrate this point. In the semi-conductor sector, out of the top-ten firms *Toshiba* and *IBM* are present in all three sub-periods, with *Toshiba* being dominant both in terms of degree and betweenness centrality, and *IBM* a focal actor only in terms of betweenness. This situation suggests that a dominant position is not

existing nodes that have large centrality degrees than to nodes with relatively lower degrees. And consequently, highly connected nodes become more connected over time.

[4]See Jackson and Rogers (2007) for a dynamical model of network formation generating incomplete power laws.

necessarily related to the number of alliances. In the telecommunication sector, only *Motorola* is present in the three sub-periods. This confirms the dominant role played by this company and also highlights its ranking in the three sub-periods of analysis. In the pharmaceutical sector, *SmithKline Beecham* and *Genentech* are present in all sub-periods. However, their ranking order decreased in the last sub-period. *Pfizer* and *Eli Lilly* seem to be more central in terms of betweenness centrality than *SmithKline Beecham* and *Genentech* in the last two sub-periods. When we looked at the degree centrality of *SmithKline Beecham* and *Genentech* in the first sub-period, the two firms appeared to be in a better position than *Pfizer* and *Eli Lilly*. This situation indicates that the former were dominant actors during the first two sub-periods but lost their advantage afterwards and were surpassed by *Pfizer* and *Eli Lilly*.

To sum up, the structure of the three R&D networks clearly exhibits a 'small world' structure during the first two sub-periods of analysis, which may strongly influence their potential for knowledge creation and dissemination. 'Small world' networks are locally clustered into dense sub-networks or cliques that are sparsely connected by a small number of ties that cuts across the cliques, linking network members through a relatively small number of intermediaries. The two centrality measures (degree and betweenness) show that the ranking of the top-ten firms for each R&D network is not stable and changes over time. Only a few are present in all the three sub-periods of analysis, and that is fundamental for both the creation of a 'small world' architecture and innovation (*Toshiba* and *IBM* for the semiconductor industry, *Motorola* for the telecommunication industry, and *Pfizer* and *Eli Lilly* for the pharmaceutical industry). Instability and changes in ranking emphasize the fierce competition these industries have to face up to as well as the rapid technological change that occurs in these knowledge-intensive industries.

Overall, the evolution of R&D networks over the period of analysis clearly shows that after an outburst of R&D partnerships for each network which essentially took place during the years 1992-1998 thanks to very dense R&D networks, the last sub-period is driven by some isolated dyads and clusters.

4 Discussion

Knowledge-intensive industries such as the semiconductor, telecommunication and pharmaceutical industries are characterized by both traditional price and knowledge-based oligopoly competition (Mytelka and Delapierre [1999]). Globalisation has reinforced these modes of competition as well as the innovation race. The formation of networks by firms aims to develop new knowledge and control the evolution of technological trajectories (Delapierre and Mytelka [2003]). Indeed, partnerships help to reduce costs, risks and even uncertainties in a process of continuous innovation; they are also an important source of learning and innovation (Powell, Kogut and Smith-Doerr [1996]). In this context, the decline of the number of R&D alliances, as revealed by figure 1, can be explained by, at least, two complementary reasons: first, a decrease in the innovative activity of these industries and, second, a deepening of market concentration which was eventually accompanied by a rise in M&A operations. We addressed hereinafter these points by both suggesting specific arguments and presenting adequate features.

We started with data on the patents the three industries received during the same period (1985-2005). To do so, we extracted the relevant information from the *United States Patent and Trademark Office* (USPTO) database. Figure 12 shows that the number of patents issued in the three high-tech industries is strongly correlated with the number of alliances and its subsequent a collapse with a time lag of approximately five to six years for the three sectors.

- Insert figure 12 about here -

It seems that by the end of the 1990s, innovation and the exploration of new capabilities attained a saturation threshold. However, this argument can be downplayed by the fact that the innovation projects undertaken by firms which are part of alliances is not fully representative of the innovative activity within the whole industry. Figure 13 presents the evolution of the number of patents granted to the allied firms in the total number of patents for each industry over the period.

- Insert figure 13 about here -

We found that the ratio is rather stable (even on the increase for the semiconductor industry). Therefore, the total amount of R&D cooperative agreements, and more particularly their decreasing number during the late 1990s, were strongly correlated with the innovative activity in the sectors concerned. We inferred from figures 1 and 12 that joint innovative activity was presumably representative of the innovative activity within the whole industry, and that it sharply declined during the late 1990s. To explain this decrease in innovative activity, recent empirical work (Sachwald and Miotti [2006]) asserts that around 2000, a new phase of globalisation gathered pace through a comeback of the 'old economy' sectors and concurrently caused the 'new economy' and the high-tech sectors to shrink. Hence, current economic growth is more readily driven by traditional sectors, such as machinery, automobiles (assembly, components), chemicals, foodstuffs, and the metal industry; all of these sectors being somehow revitalized by the economies of emerging countries such as China, India, Brazil, among others.

We then turned to the dynamics of market structure and investigated the recent concentration in market share. Our data are incomplete as some years are missing in the telecommunication industry . We computed the Herfindhal index for the ten highest market share figures in each sector and collected data for each year (therefore neglecting residual market share). Figure 14 indicates an increase in the concentration index for the semiconductor and pharmaceutical sectors; the available data in the telecommunication sector suggest an increase after 2001.

- Insert figure 14 about here -

These converging results confirm the recent evolution toward a more concentrated structure in the sectors concerned. In parallel, we measured the evolution of M&A operations involving a target firm in each sector as of 1990. As a result, figure 15 displays a continuous increase in the measure for the pharmaceutical industry, an upward trend between 1998 and 2000 for the semiconductor sector, and an increase until 2000 followed by a fall afterwards in the telecommunication sector.

- Insert figure 15 about here -

Accordingly, the dynamics of M&As gives part of the explanation for the recent increase in concentration for the semiconductor and pharmaceutical sectors. The first reason why the high-tech sectors recently became more concentrated seems to be reflective of the dwindle in innovative activity. This trend is supported by the surge in M&A operations, which were often preferred to strategic alliances as external sources of innovative capabilities in the firms' core businesses. This view is confirmed by some studies which have documented that M&As are negatively correlated with the industry's growth rate (Hennart [1988], Hagedoorn and Sadowski [1999], Vanhaverbeke *et al.* [2002]). As a matter of fact, M&As do not only bring size into the considerations associated with the range of products and markets in which a firm can be present, but also new R&D, design and engineering capabilities. Therefore, M&As contribute to the flexibility with which firms can provide new solutions to their clients in the long term.

The second reason results from the overarching globalisation process through the emergence of institutional change such as extensive deregulation policies and the opening to domestic and foreign competition. Obviously, deregulation has hit many sectors like air transportation and telecommunications, more particularly. Furthermore, deregulation in telecommunications together with the pressure of more competitive markets prompted telecommunication operators to invest on a large scale. Concurrently, the move from monopolistic to competitive markets, robust economic growth and the development of real innovative services (electronic commerce) have fed the 'Internet bubble'. Battered by overinvestment, the telecommunication operators were unable to achieve their forecast objectives. So, the bubble eventually burst and the sector fell in crisis. Revenues as well as production targets were downgraded and, eventually, investment expenses were reduced. As they were strongly reliant on telecommunication operators, the telecommunication equipment suppliers have also suffered from the operators' drastic curb on investment. In addition, size has become a prominent consideration in the way firms compete for survival, as illustrated by recent big-ticket mergers (*Alcatel/Lucent*, *Nokia/Siemens*).

5 Conclusion

We have thoroughly described the dynamics of worldwide R&D networks in three high-tech sectors (semiconductors, pharmaceuticals and communications equipment). Our analysis points out that, beyond the specificities of each industry, the dynamics of R&D network formation is, in the end, not industry-driven. This is to some extent surprising, as the parameters controlling both the technological potential and the turbulence of innovation, as well as the profitability of economic actors is largely industry-sensitive. Our analysis also reveals a dramatic fall in the number of R&D partnerships after the mid-1990s. One straightforward result is that the collapse of R&D partnerships was accompanied by market concentration. Hence, the study supports the view that the development of R&D cooperative agreements spurring innovation in high-tech industries is sensitive to the nature and the stage of the life-cycle of innovation within the industry.

Although the pursuit lies beyond the scope of this paper, the findings raise several questions which deserve further attention. The first issue concerns the extent to which the database content is reliable. The drastic fall in detected R&D partnerships after 2000 may after all, be only partly either due to less systematic tracking for exogenous reasons, or simply be the result of the drop in publicly declared alliances by the firms concerned. Further studies may therefore be needed to determine to what extent our statement can be upheld. The second issue relates to the extent of the respective impact of, on the one hand, the international economic environment and, on the other, the recent slowdown in these industries' technological innovation potential. The third issue deals with the on-going deregulation process, at national and transnational levels, and the advance of globalisation, both of which factors must be viewed as permissive. In this context, we may suspect that globalisation could affect the evolution of contracting practices even more.

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APPENDIX A: DATA

For this study, we used two databases. First, we resorted to SDC Platinum (Thomson Financial), a database which collects information on R&D partnerships from public announcements. This database has the advantage of containing a large number of alliances (it encompasses the main high-tech sectors and holds probably 3 or 4 times more alliances than the MERIT-CATI database). In addition, it monitors the formation of new alliances over time more systematically, although it probably focuses more on the alliances that have U.S. firms as partners. Basically, the database contains a lot of information on various types of agreements, such as marketing, commercial, R&D, or manufacturing agreements. We concentrated here on R&D agreements only. We extracted from the database the details containing the alliance announcement date, the partners' names and their SIC codes, the nature of the agreement, the name of the firms' home country, the name, country and SIC codes of their parent firms. Note that the database is constantly updated, which enabled us to obtain fresh data. The present paper is actually concerned with the partnerships established over the 1985-2005 (included) period. The pharmaceutical sub-base contains 3,648 alliances over the period, the semiconductor's 1,592, and the communications equipment sub-base 798. When an alliance contained $k \geq 3$ partners, we chose to substitute it with the $\frac{k(k-1)}{2}$ alliances corresponding to the maximal set of distinct pairs among all members.

Second, we used the USPTO database which is continuously updated and in free access. We assigned patents to the year of application, and extracted data for the same period as previously. The database takes in the patents granted on the U.S. market to companies and academic bodies. This could be a problem for our analysis and the results we have used, since two other prominent markets (the European Union and Japan) are out of reach, but it is somehow consistent with SDC Platinum's foregoing bias in favor of U.S. companies on the one side and the large number of foreign companies as assignees present in the USPTO database on the other.

APPENDIX B: TABLES

Table 1a: Characteristics of the R&D networks for each seven-year period

	Semiconductor			Pharmaceutical			Telecom		
Period	85-91	92-98	99-05	85-91	92-98	99-05	85-91	92-98	99-05
Number of firms	174	375	83	449	1099	167	157	471	30
Number of alliances	161	384	41	411	1419	92	157	706	26
Average degree	2.02	2.58	1.25	1.84	2.61	1.11	1.88	2.54	1.13

Table 1b: Characteristics of the greatest (giant) component for each seven-year period

	Semiconductor			Pharmaceutical			Telecom		
Number of firms	77	234	8	272	822	6	80	269	3
As percentage	44.25	62.4	9.64	60.58	74.8	3.6	50.95	57.11	10
Average degree	2.93	3.38	2.50	2.23	3.08	2.67	2.55	3.49	1.33
Av. path length	3.72	3.90	2.25	8.30	5.17	1.53	4.55	4.24	1.33
Av. path length stoch. net.	4.03	4.47	2.27	6.00	5.96	1.83	4.68	4.48	3.82
Ratio av. path length	**0.92**	**0.87**	**0.99**	**1.18**	**0.87**	**0.84**	**0.97**	**0.94**	**0.35**
Av. Clustering coef.	0.39	0.39	0.58	0.17	0.2	0.75	0.26	0.48	0
Av. Clust. coef. stoch. net.	0.006	0.002	0.06	0.008	0.004	0.53	0.03	0.01	0.67
Ratio clustering	**63.87**	**169.83**	**10.25**	**21.04**	**53.22**	**1.41**	**8.08**	**36.58**	**0**

Table 2a: Top-ten degree centrality in Semiconductor R&D network

85-91	92-98	99-05
Texas Instruments Inc (15)	Intel Co (25)	Taiwan Semiconductor Mnfr Co (4)
National Semiconductor Co (11)	Toshiba Co (24)	STMicroelectronics NV (3)
Fujitsu Ltd (10)	NEC Co (22)	Koninklijke Philips-CDMA Asset (3)
Intel Co (8)	Siemens AG (20)	IBM Co (3)
VLSI Technology Inc (8)	Fujitsu Ltd (19)	Motorola Co (3)
Toshiba Co (7)	Texas Instruments Inc (15)	Toshiba Co (3)
Motorola Inc (7)	Hitachi Ltd (15)	Cadence Design Systems Inc (2)
EXAR Co (6)	Sony Co (14)	Intel Co (2)
General Instrument Co (6)	SGS-Thomson Microelectronics (14)	Infinesse Co (2)
Sony Co (6)	LSI Logic Co (13)	Sony Co (2)

Table 2b: Top-ten degree centrality in telecommunication R&D network

85-91	92-98	99-05
Motorola Inc (15)	IBM Co (26)	Motorola Inc (2)
American Telephone & Telegraph (12)	Intel Co (23)	Versa Technologies Inc (2)
Nippon Telegraph & Telephone (10)	American Telephone & Telegraph (21)	NTT DoCoMo Inc (2)
NEC Co (10)	Motorola Inc (19)	JVC (2)
Fujitsu Ltd (8)	Hitachi Ltd (18)	Harris Co (2)
Digital Equipment Co (7)	NEC Co (18)	Mitsubishi Electric Co (2)
SynOptics Communications Inc (6)	BellSouth Co (17)	Omron Co (2)
Matsushita Commun Industrial (5)	MIT (16)	Nomura Research Institute (2)
Mitsubishi Electric Co (5)	Mitsubishi Electric Co (15)	AboCom Systems Inc (2)
Cabletron Systems Inc (5)	Microsoft Co (15)	Tateck (2)

Table 2c: Top-ten degree centrality in Pharmaceutical R&D network

85-91	92-98	99-05
Genentech Inc (12)	Eli Lilly & Co (31)	Pfizer Inc (4)
Bristol-Myers Squibb Co (8)	SmithKline Beecham PLC (28)	Eli Lilly & Co (4)
Calgene Inc (6)	Chiron Co (24)	Millennium Pharmaceuticals Inc (3)
Warner-Lambert Co (6)	Rhone-Poulenc Rorer Inc (22)	Astra AB (3)
Schering-Plough Co (6)	Pfizer Inc (21)	Chiron Co (3)
Yamanouchi Pharmaceutical Co (6)	Abbott Laboratories (20)	Ortho-Clinical Diagnostics Inc (2)
Merck KGaA (5)	Bristol-Myers Squibb Co (18)	OSI Pharmaceuticals Inc (2)
SmithKline Beecham PLC (5)	Merck & Co Inc (18)	Nordmark Arzneimittel GmbH (2)
Biogen Inc (5)	Genentech Inc (18)	Neurobiological Technologies (2)
Eli Lilly & Co (5)	NHI (16)	Bristol-Myers Squibb Co (2)

Table 3a: Betweenness centrality in Semiconductor R&D network

85-91	92-98
Fujitsu Ltd	Intel Co
Texas Instruments Inc	Toshiba Co
Toshiba Co	Texas Instruments Inc
Hitachi Ltd	IBM Co
Sony Co	Siemens AG
VLSI Technology Inc	NEC Co
MIPS Computer Systems Inc	LSI Logic Co
Siemens AG	VLSI Technology Inc
National Semiconductor Co	National Semiconductor Co
IBM	Motorola Inc

Table 3b: Betweenness centrality in Telecom R&D network

85-91	92-98
Motorola Inc	Intel Co
American Telephone & Telegraph	IBM Co
Digital Equipment Co	American Telephone & Telegraph
Nippon Telegraph & Telephon	NEC Co
Cabletron Systems Inc	Mitsubishi Electric Co
NEC Co	Motorola Inc
SynOptics Communications Inc	Northern Telecom Ltd
Data General Co	SynOptics Communications Inc
Wellfleet Communications	Hitachi Ltd
SGI	Cisco Systems Inc

Table 3c: Betweenness centrality in Pharmaceutical R&D network

85-91	92-98
Genetics Institute Inc	Eli Lilly & Co
Genentech Inc	SmithKline Beecham PLC
Hoffmann-La Roche Inc	Chiron Co
Baxter Healthcare Co	Abbott Laboratories
SmithKline Beecham PLC	NHI
Organon Teknika BV (Akzo Nobel)	Schering-Plough Co
Epitope Inc	Merck & Co Inc
Takeda Chemical Industries Ltd	Rhone-Poulenc Rorer Inc
Bonelli e Associati,Pappalardo	Pfizer Inc
Schering-Plough Co	Genentech Inc

APPENDIX C: FIGURES

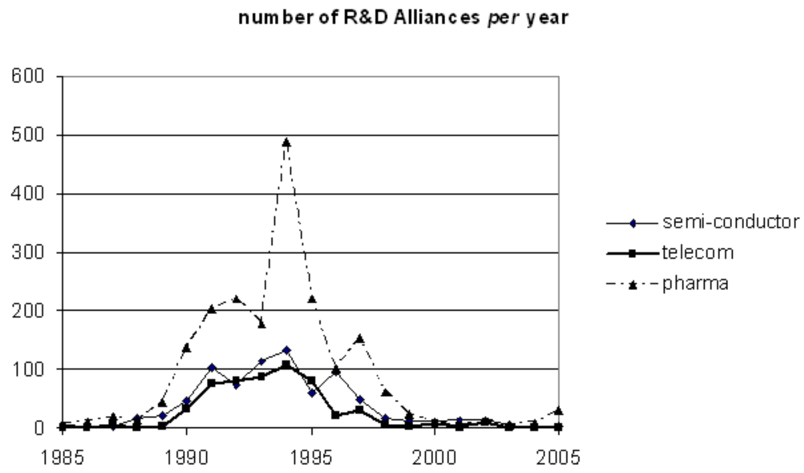

Figure 1: Number of R&D alliances *per* year

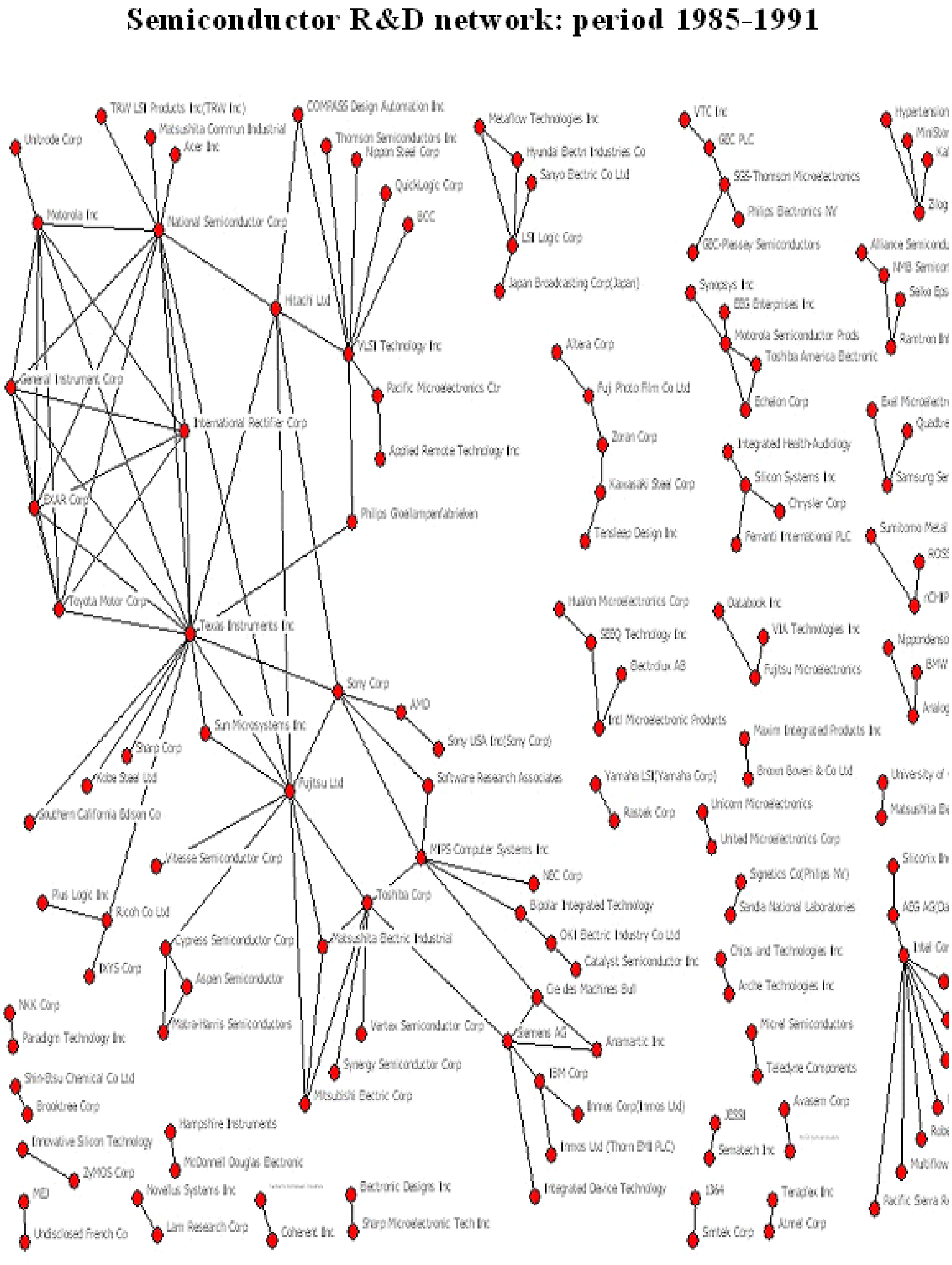

Figure 2: R&D Network in semiconductor industry; period 1985-1991

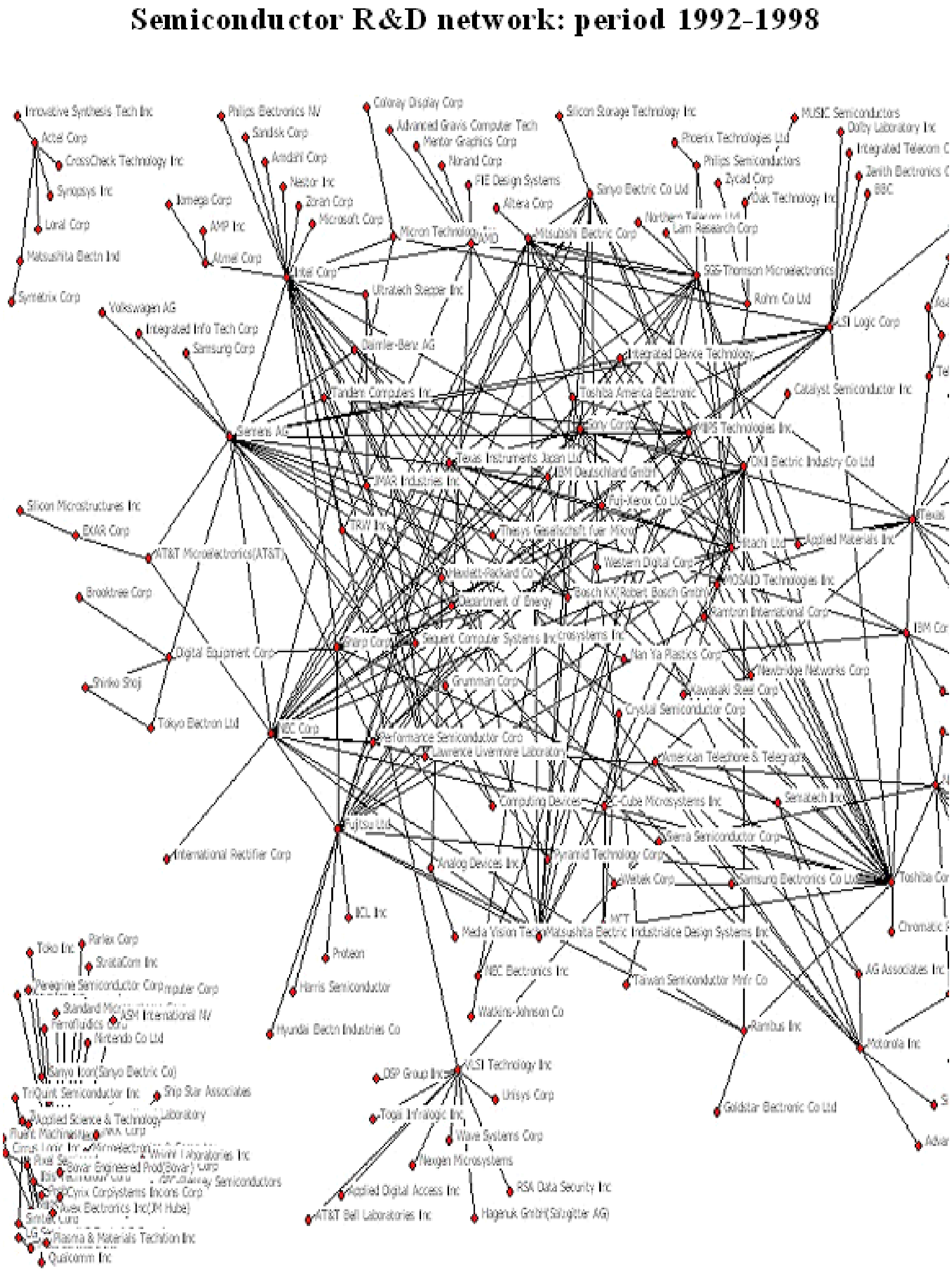

Figure 3: R&D Network in semiconductor industry; period 1992-1998

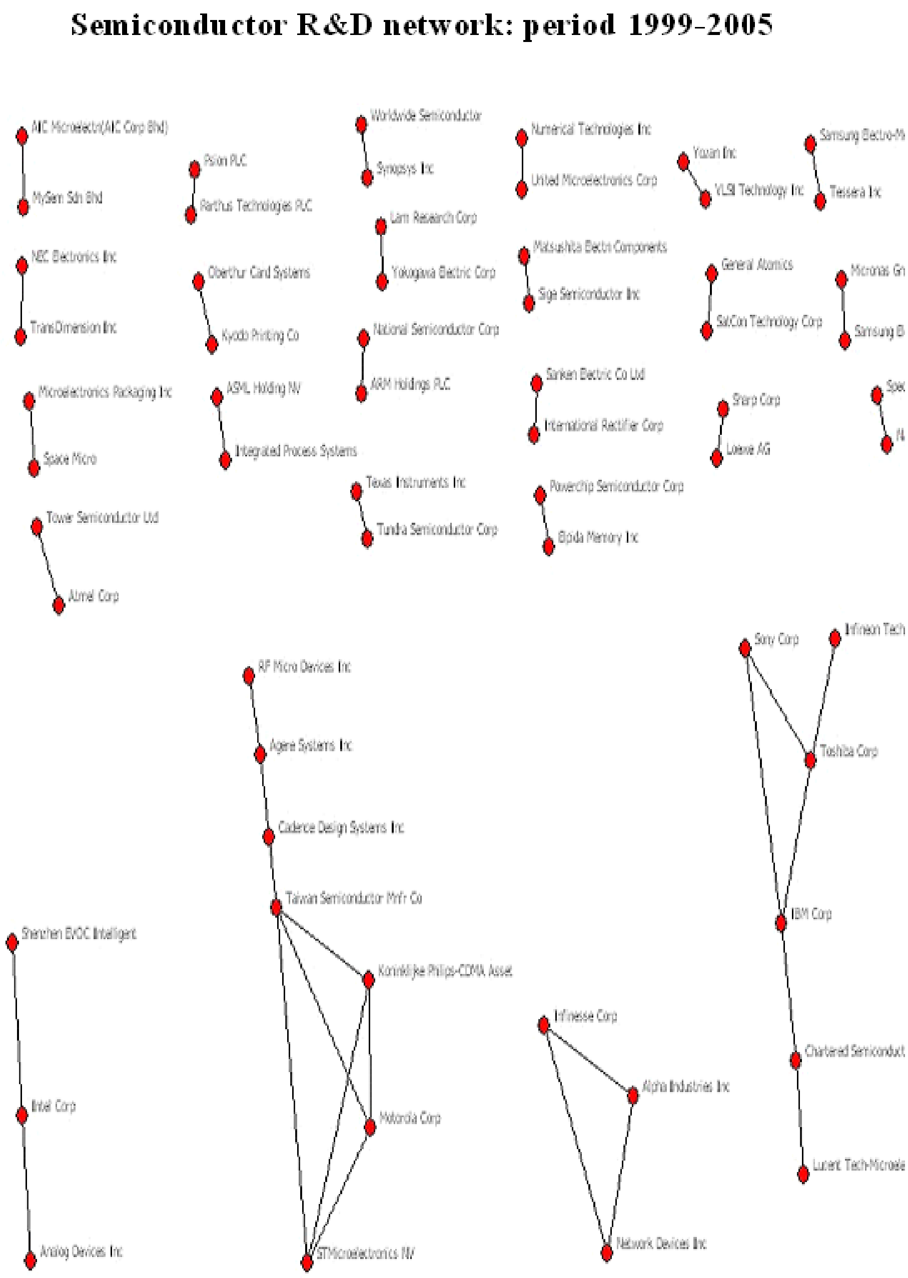

Figure 4: R&D Network in semiconductor industry; period 1999-2005

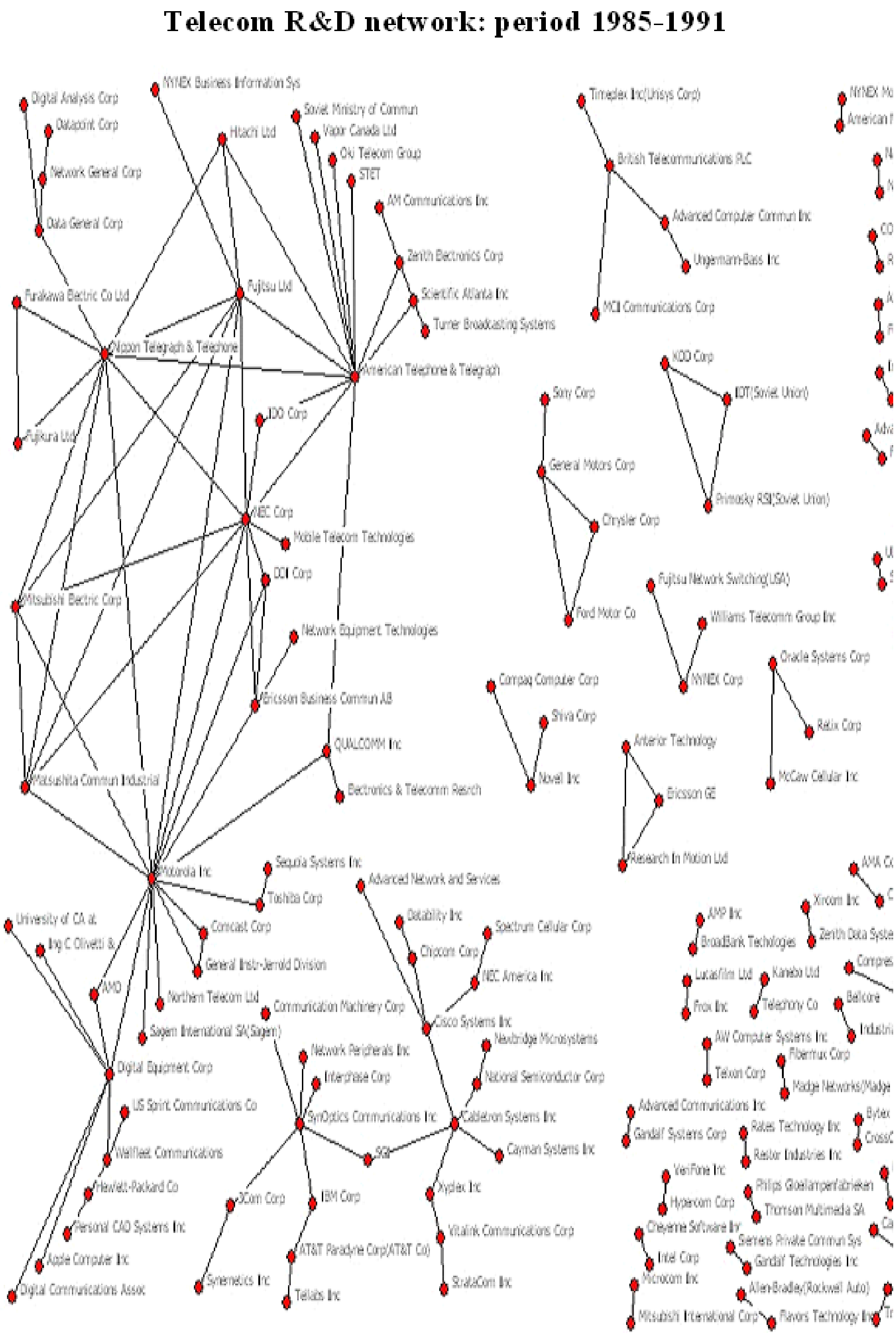

Figure 5: R&D Network in telecommunication industry; period 1985-1991

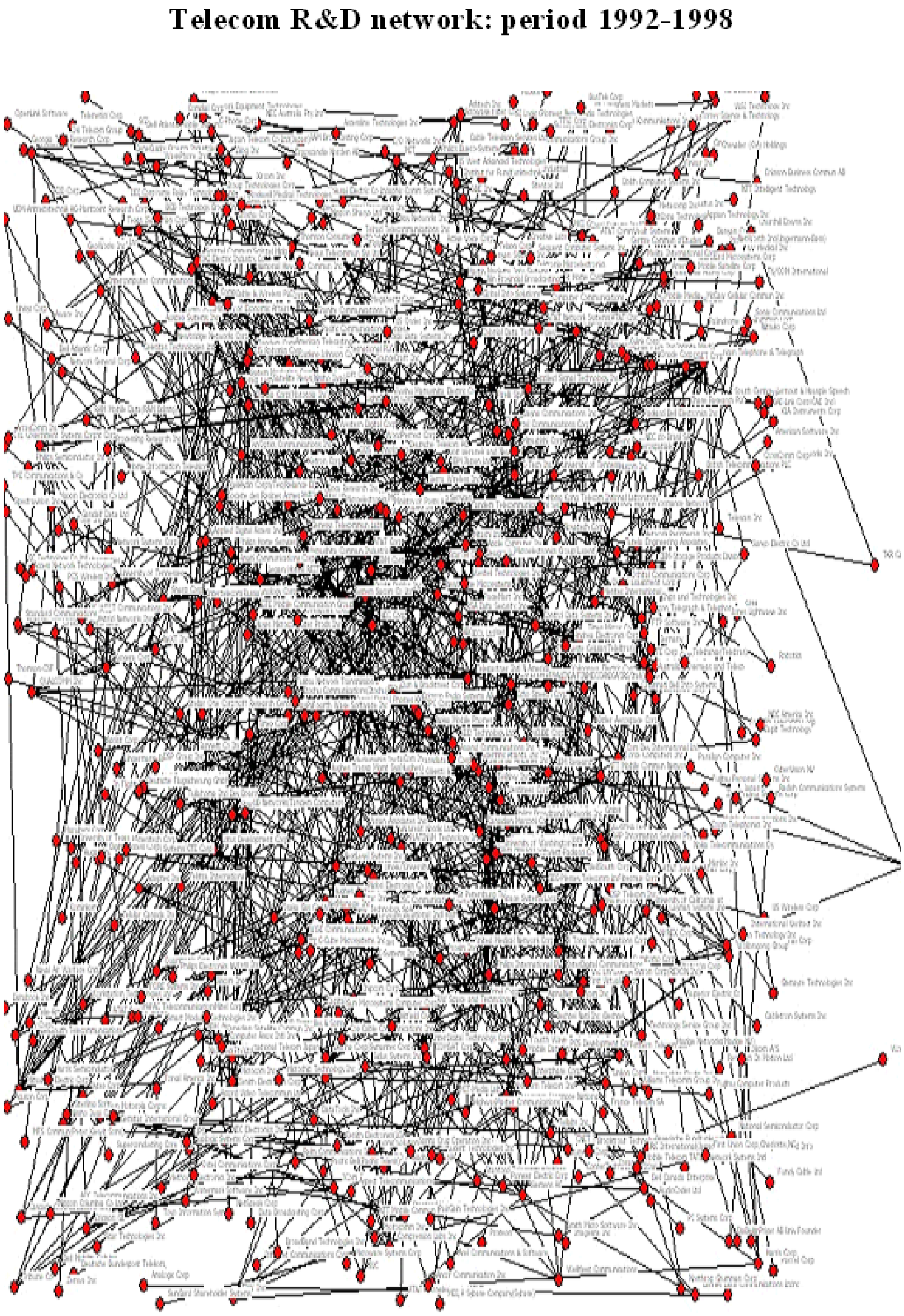

Figure 6: R&D Network in telecommunication industry; period 1992-1998

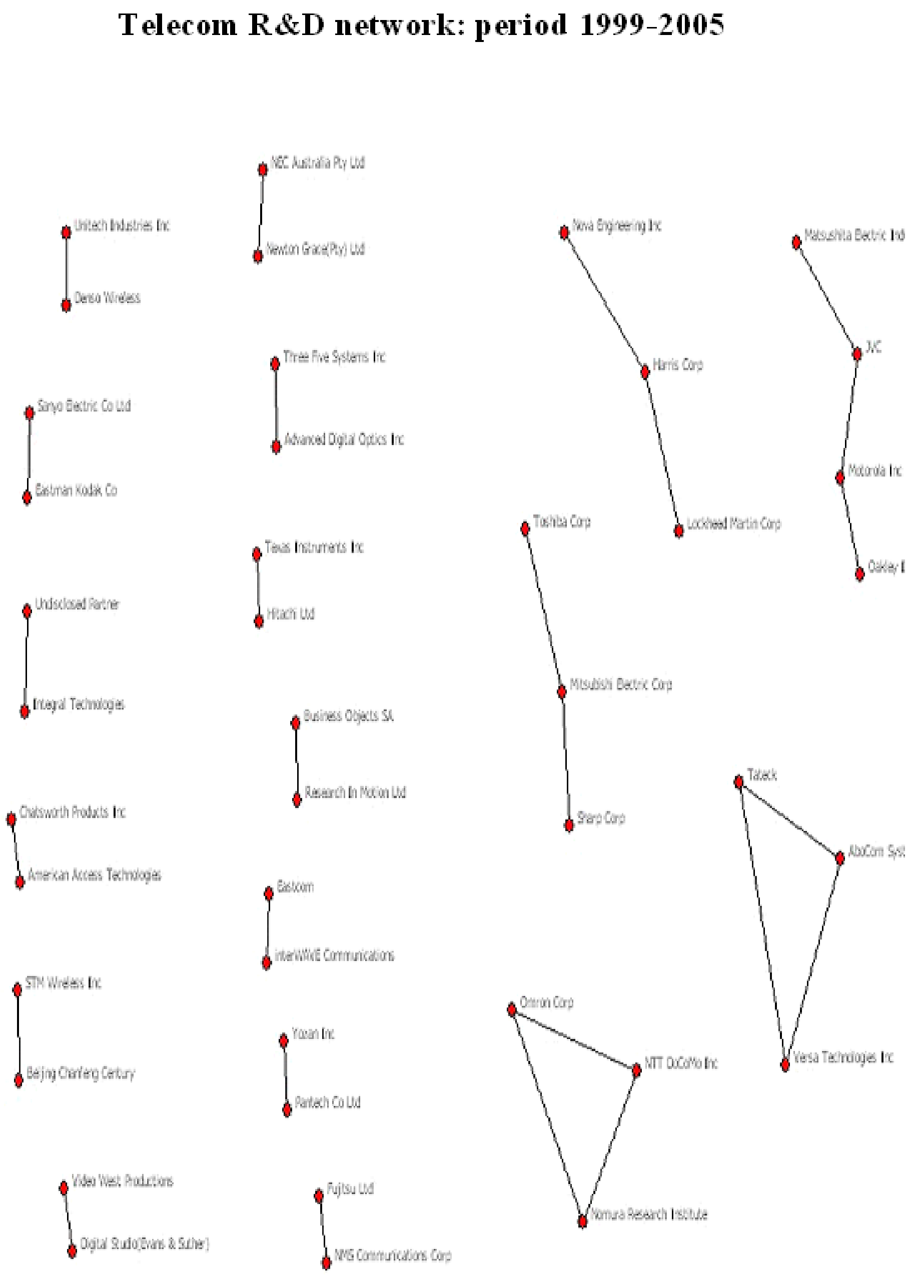

Figure 7: R&D Network in telecommunication industry; period 1999-2005

Figure 8: R&D Network in pharmaceutical industry; period 1985-1991

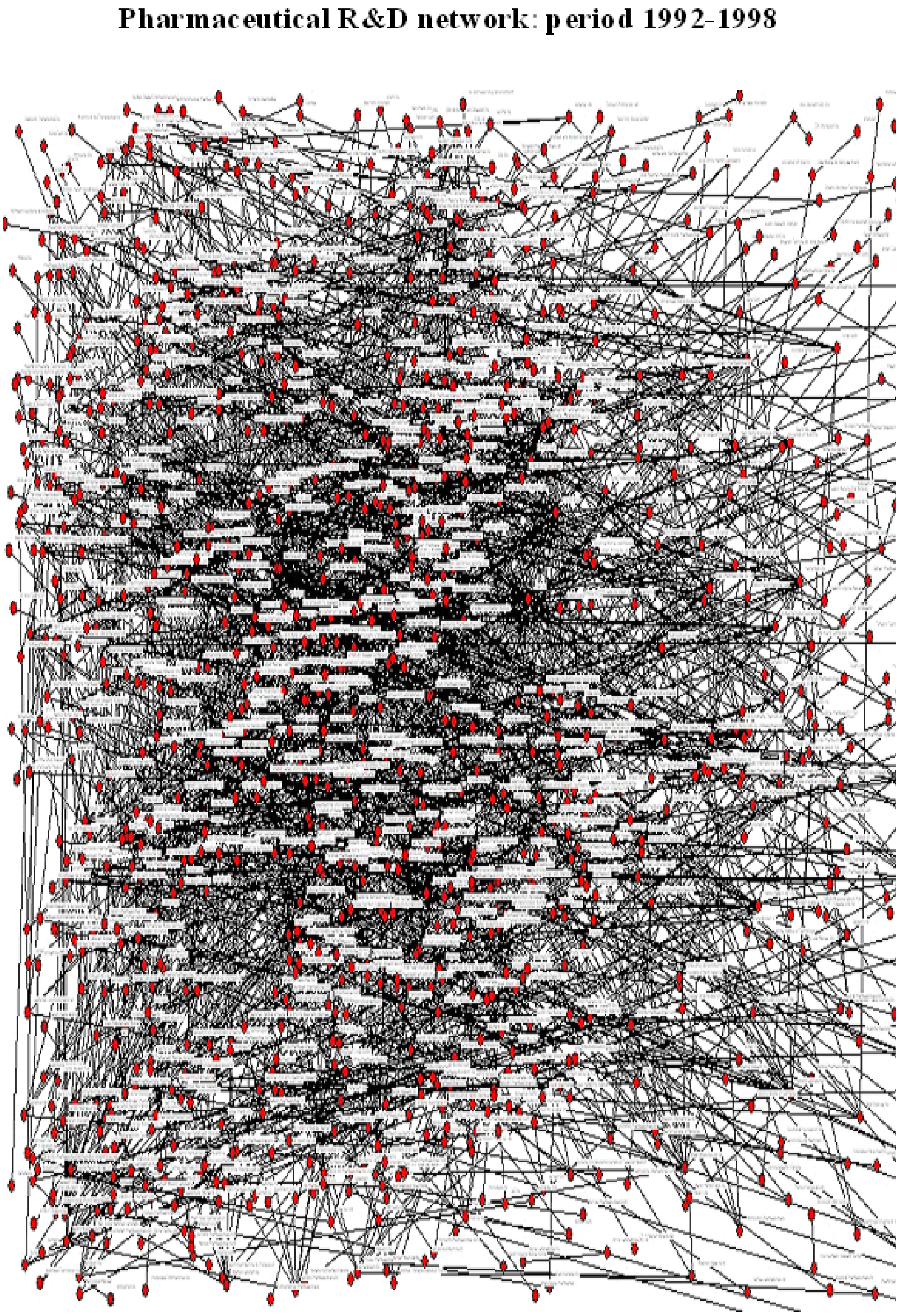

Figure 9: R&D Network in pharmaceutical industry; period 1992-1998

Pharmaceutical R&D network: period 1999-2005

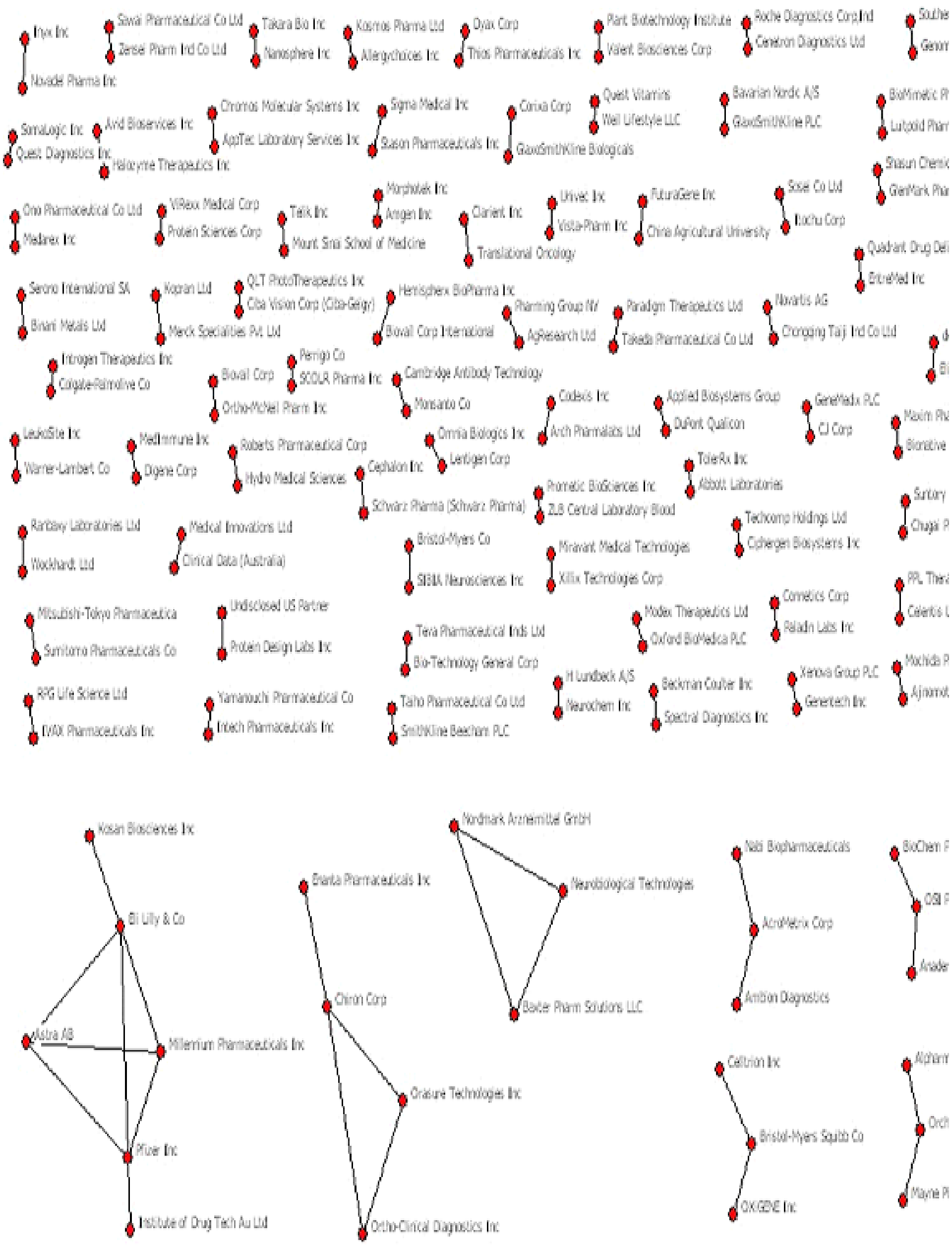

Figure 10: R&D Network in pharmaceutical industry; period 1999-2005

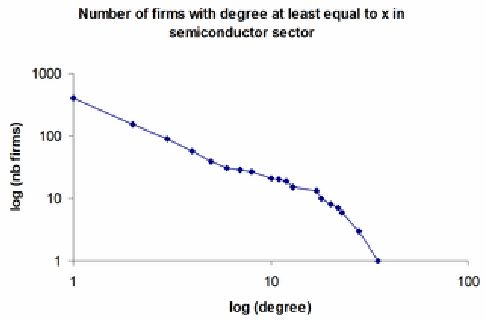

Fig 11a. Degree distribution for Semiconductor R&D network

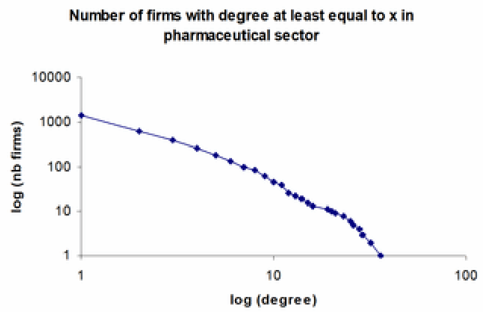

Fig 11b. Degree distribution for Pharmaceutical R&D network

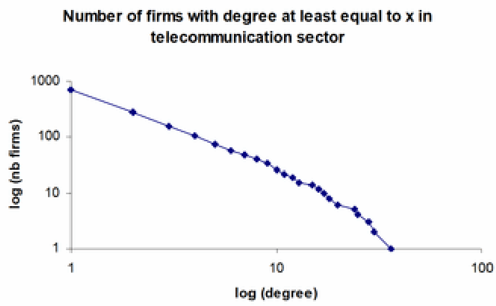

Fig 11c. Degree distribution for Telecom R&D network

Figure 11: Degree distribution in log-log scale for the three industries

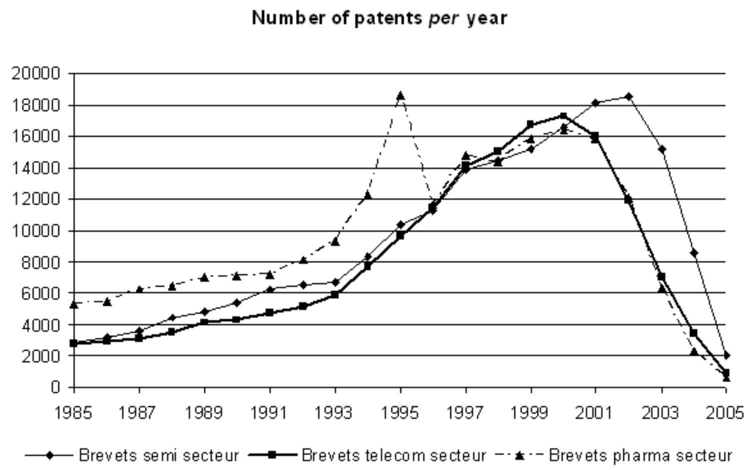

Figure 12: Number of patents *per* year for the three sectors

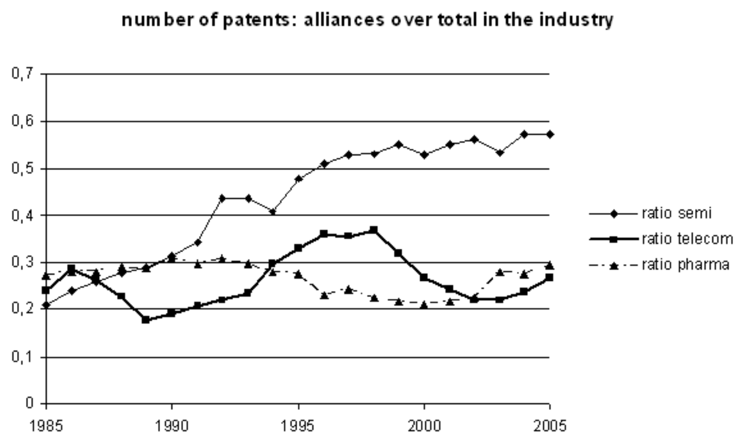

Figure 13: Ratio of the number of patents by alliances firms over the total number of patents issued in the related industry

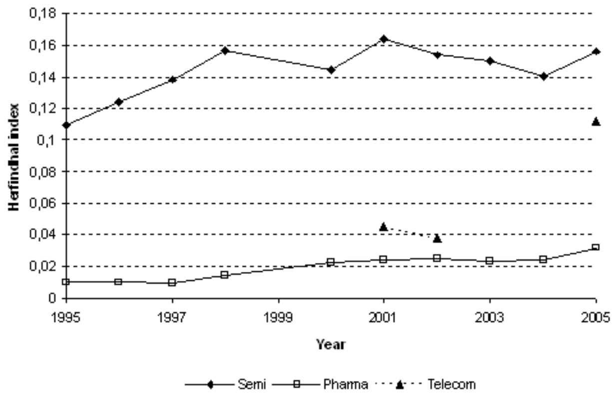

Figure 14: Evolution of concentration indexes in the related industry

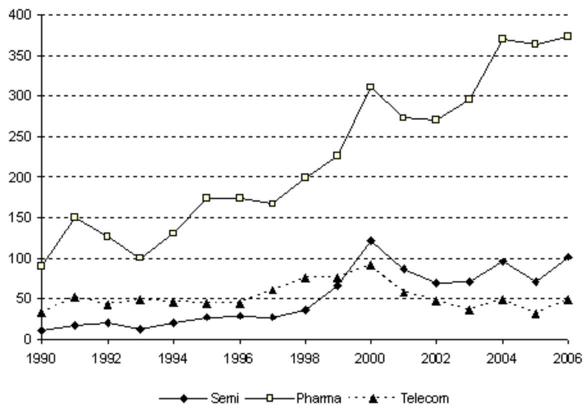

Figure 15: Evolution of the number of M&As involving a firm of each sector as a target in the related industry