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University–industry interactions in applied research: The case of microelectronics

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Abstract

In the first part of the paper we discuss the pattern of research in microelectronics, illustrating the reasons why, in order to achieve distinguished scientific performance, universities need to collaborate with industry, and in particular academic researchers need to interact with industrial ones by face-to-face knowledge exchanges. In the second part, using patent data integrated with information collected through interviews, we measure the extent and intensity of the ties of academic with industrial researchers, and apply social network analysis to reconstruct the network of collaborations. The picture that emerges (from this Italian case) is fully consistent with the specific research pattern. Collaboration is based on teams of researchers from the two spheres, and strong connections are associated with high scientific performance. Moreover, border-crossing collaborations tend to be driven by cognitive proximity and personal relationships.

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1. Introduction

A clear account of the goals and patterns of research that characterise particular fields is a necessary premise to understand why the relationships between university and industry may be important or even necessary. A fundamental contribution in this direction was offered by Rosenberg and Nelson (1994) and Nelson and Rosenberg (1998) who pointed out that a large part of the scientific or engineering disciplines that are currently embodied in academic curricula was developed precisely to meet the knowledge and education requirements of firms. Moreover, academic researchers working in these applied fields must be "intimately familiar" with industrial technology (Klevorick et al., 1995) in order to be able to create significantly new designs, concepts, methods and prototypes. However, to make their contribution to the advancement of technology, they also need to search for fundamental understanding and to be involved in other issues that are usually associated with basic research, such as deep questions of logic, computation, and very complex and refined scientific methodologies. Thus, the scientific standing of academic researchers in these disciplines does not necessarily conflict with their intimacy with technology, which can be achieved only through direct contacts and collaborations with industry.

Similarly, Berman (1989), Meyer-Krahmer and Schmoch (1998), Kaufmann and Tödtling (2001), and more recently Gulbrandsen and Smeby (2005), among others, have shown that in these fields collaboration and interaction between universities and firms, giving rise to two-way knowledge flows, is highly beneficial and of mutual advantage.

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In this article we attempt to contribute to these strands of literature in two directions. Firstly, building on the view of Rosenberg and Nelson (from now on RN), we discuss the nature of applied research and the degree to which it is endogenous to the economic system, with special reference to the field of microelectronics, and attempt to shed some light on the exchanges taking place in the collaboration between university and industry. Secondly, from the main characteristics of the process of creation of new scientific and technological knowledge requiring continuous interactions between university and industry, we derive some testable hypotheses that we seek to validate. The hypotheses put forward are the following: (i) the best academic centres of research are those more closely connected to industry; (ii) the interactions are founded on research teams, comprising both industrial and academic researchers, engaged in face-to-face knowledge exchanges, and give rise to a well connected network; (iii) links with strongly connected, qualified universities are particularly useful to firms for effective recruiting (i.e. they allow firms to hire productive individuals as researchers or designers); (iv) border-crossing connections linking individual researchers of the two spheres tend to be driven by cognitive proximity and personal relationships.

The data gathered to carry out our empirical analysis refer to the Italian system of research and innovation in electronics. We mainly used patent data, focusing on the teams of co-inventors including at least one Italian academic researcher among the industrial ones, and supplemented them with (a) bibliometric data on the scientific productivity of all Italian academic centres engaged in the field of electronics, (b) information on the working position of co-inventors obtained by interviewing all Italian academic professors co-authoring patents applied for by firms, and (c) data on the graduates in electronics from the Italian university most closely connected with industry (the University of Pavia).

By applying social network analysis to the data we had collected, we were able to formally reconstruct a significant network connecting Italian professors of electronics with industry, to 'recognise' the nodes (be they academic or industrial, having graduated or not from a university closely connected with industry) and to analyse their ties (in terms of persistency, direction and involvement of personal relationships). The story of beneficial interaction which step by step comes to light clearly conforms to the model of applied academic research depicted at the beginning of the paper and the expectations it elicited.

2. 'Applied' academic research revisited

In the past 20 years the linear model, which considers technology as a mere application of prior scientific knowledge, has been broadly criticised, as has the associated dichotomy between basic and applied research, whereby the former pursues the goal of fundamental understanding with no concern for applications, while the latter simply focuses on practical purposes. An inherent tension between the goals of understanding and use is supposed to keep the two categories of research separate.

Rosenberg (1976, 1982), Rosenberg and Nelson (1994), Nelson and Rosenberg (1998) and Stokes (1997), the most authoritative critics of that vision, have made it clear that basic research that seeks to extend the frontier of understanding is often inspired by considerations of use; that technology is itself a body of knowledge that proceeds along a trajectory of its own, and not merely the application of knowledge taken from another sphere ("it is a knowledge of techniques, methods, and design that work, and that work in certain ways and with certain consequences, even when one cannot explain exactly why", according to Rosenberg (1982, p. 143); and that technology has often shaped science by providing data that became the explicanda of scientists.

In particular, Stokes introduced the concept of use-inspired basic research, epitomised by the mature Pasteur, who was consistently committed both to understanding the microbiological processes he discovered and to controlling the effects of these processes on various products as well as on animals and humans. Thus, this is a type of research that lies in between purely basic (epitomised by Bohr) and purely applied (Edison's case) research, and which often casts a bridge between the 'loosely coupled', interactive but semi-autonomous trajectories of science and technology.

Thus, human needs – such as the need to cure diseases – come into play, inspiring the work of scientists, as in the case of research related to the solution of clinical problems or that concerned with basic biological or chemical mechanisms.

It is worth noting the difference between this conceptual proposal and the vision of Rosenberg (1976, 1982). Instead of focusing on the motivations of scientists and the lack of tension between basic understanding and consideration of human needs, he introduced the issue of science being endogenous to the economy, and stressed the importance of understanding the degree to which science is a social activity responsive to economic forces. Thus, the agenda of scientists is influenced by human needs not directly, but as they become articulated through changing technological artefacts. In particular, high-technology industries, by pushing against the limits of technical performance, continually identify the directions of new scientific research and are a major determinant of the allocation of scientific resources.

These two different views do not seem to be in contrast, but rather refer to the evidence drawn from different scientific disciplines, life sciences on the one hand and the 'sciences of the artificial' on the other. The latter comprise the engineering disciplines, which currently constitute a large part of academic curricula, and whose design orientation does not exclude important basic aspects with regard to the methodologies applied and the quest for understanding the fundamental causes that determine the functioning of material artefacts. In these fields, academic research is aimed precisely at facilitating technical progress, offsetting "the depletion of the pool of technological possibilities in the industries toward which the efforts are directed" (Klevorick et al., 1995). In fact, scientific developments directly open up new technological opportunities, pointing to promising new avenues, and are often the source of radically new concepts and designs, many of them suitable to be embodied into prototypes.

It is the very nature of these fields, which produce knowledge directly relevant to industry that makes collaboration between industry and universities essential. As a recent stream of empirical research (quoted in the preceding section) has shown, the links between universities and industry consist of two-way knowledge flows that demand face-to-face interaction. Moreover, academic researchers typically integrate scientific and technological activities, generating scientific papers as well as technological outputs (patents), and in a large majority of cases have continuing consulting relationships with at least some of the firms supporting their academic research (Mansfield, 1995). Finally, collaboration provides a very important training for the students involved (Berman, 1989) and offers companies a crucial instrument for recruiting.

Of course, this collaborative research is not a substitute for more practical and specific research typically performed within industry (Rosenberg and Nelson, 1994). Strong incentives and deep-rooted cultural factors tend to lead to the establishment of a fruitful division of labour. The results of specific research are in general appropriated by industry, which therefore might be reluctant to share them with academic researchers cooperating with more than one company. Moreover, they are not useful to the scientific reputation and career of academic researchers, which is based on publications on refereed journals. The risk that companies might entirely divert the attention of academics (with pecuniary incentives) to specific problem-solving – turning them into mere consultants – seems to be especially related to a low academic standing of the latter.

3. The pattern of research in microelectronics

The field of microelectronics clearly exemplifies the research pattern characterising the sciences of the artificial, shedding light on the rationale for both the collaboration and the division of labour between university and industry.

To exploit the opportunities generated by the increasing miniaturisation and density of semiconductor devices, new circuit designs, systems and applications must be created incessantly. To circuit designers (both academic and industrial) this entails a host of new interesting problems that need a solution and to firms the possibility of profiting by a sustained market growth, thanks to the supply of new products.

The main aspect which differentiates academic from industrial research is the level of risk born, involved in the complexity and especially the distance of explorations from existing markets and known technical solutions.

The riskier explorations are performed by the 'institution of science', and are supported by public funding. Typically, academic researchers are concerned with radically new problems, with the aim of either creating new products or demonstrating that new unexpected applications can be realized also by resorting to known technologies or by creatively recombining existing concepts. Unconstrained by the pressure of market demands, they enjoy a much broader freedom to set their own research agenda than their industrial counterparts. However, since the ultimate sense of their work is to set the foundations for the creation of products which will function and will have a market in the future, they need a link with industry to orient their efforts towards directions that are believed to be fruitful in terms of broad evolving trends of the market. Thus they look at industry for 'direction' in general, and more specifically for problems to be solved (such as the so called 'brick walls' which hinder technological development in certain areas). This fundamental aspect makes this field of research endogenous with respect to the economic system.

The methods employed by academic researchers are scientific in character, as they involve innovative methodologies, new theories and mathematical formalizations of the problems addressed, and a full analytical understanding of the fundamental limits of circuits, in order to avoid wasting time in attempting to overcome them. But the research process is facilitated by face-to-face interactions with industrial researchers, since the more technical culture of the latter is complementary to the more analytical approach of academics. Industrial researchers are able to indicate and supply tools – such as 'libraries' of circuit blocks, design kits and CAD tools – which are very important to speed up research and to allow researchers to concentrate on the real novelties. Thus academic researchers are networked with the most advanced industry teams.

The less risky explorations involve replicating old products in enhanced versions, targeting already existing and well known markets (e.g. microprocessors or memories for PCs), and are conducted by firms under the strict time constraints set by specific market requirements. In between, one finds research with the goal of realising either new applications in fields which are already being exploited (e.g. certain types of wireless applications), or drastically enhanced versions of existing products, which are however predictable in both technological and commercial terms (e.g. hard disk drives with an internal data rate extended beyond 2 GSps – Giga Samples per second – from 850 MSps). This medium-run research is usually conducted by industrial research teams expressly isolated from the pressures of current needs, and increasingly located inside university campuses.

Finally, specific of industry is the task of transforming original prototypes into final products, by industrialisation and customisation. At this stage, knowledge turns from general to specific (adapted to clients' needs), through a specialised problem-solving effort and know-how.

Universities require firms' cooperation not only to exchange knowledge, but also to get funding and to access production technologies, in order to get prototype chips manufactured (Balconi and Centuori, 2004). The latter must in fact be physically tested, to get the measures necessary to validate the underpinning models or to indicate the need for modifications and improvements.

With regard to firms, collaboration with universities is fundamental to access highly qualified engineers. The best way to recruit them is by directly testing their abilities during joint research. Ideas, solutions to problems, models delivered by university professors are also very important, and the establishment of direct personal links allows firms to tap professors' know-how. Ultimately, joint research with universities allows companies to leverage matching research funds from government.

The considerations made so far may be synthesised in the following framework (Fig. 1).

The analysis developed above suggests the following inferences, which can be submitted to empirical validation:

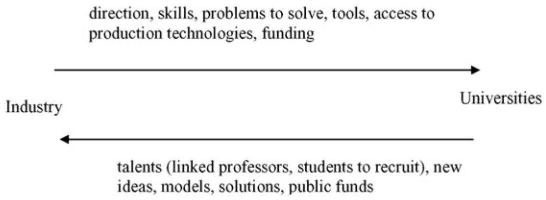

Fig. 1. The exchange between universities and industry in the field of microelectronics.

(i) In the field of microelectronics, the highest ranking academic centres in terms of scientific performance are those which include the professors most closely connected to industry.
(ii) The connections are founded on research teams comprising both industrial and academic researchers, engaged in continuous face-to-face knowledge exchanges.
(iii) The connections to qualified universities are useful to firms for effective recruiting (i.e. they allow firms to hire productive individuals as researchers or designers).

Moreover, professors are likely to have a wider variety of links than industrial researchers, due to the continuous inflow of students (both final year students and graduates) in their research teams and to their greater freedom to set their own research agenda and to choose collaborators. Thus productive academic researchers, working over time with many teams, should play an important role of connectors in the epistemic community. A related question which deserves being explored is to what extent universities' connections with industry are mediated by graduated industrial researchers who remain linked over time with their former professors, due to the importance of cognitive proximity and personal ties. To address these final issues, in the last part of the paper we shall reconstruct and analyse the network of industrial and academic researchers cooperating in producing inventions.

4. The scientific standing of academic research centres linked with industry

To address the first hypothesis, we need to measure (i) the intensity of collaboration between Italian professors of electronics and industry, and (ii) the scientific performance of professors. As an indicator of collaboration we used the number of both EPO and USPTO patents[1]

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[1] The count was done by matching the name of all Italian professors in electronics with a tenure in the year 2000 with the name of Italian inventors of (1) EPO patent applications from 1979 to the beginning

Table 1
The scientific and technological performance of the academic centres of electronics in Italy

Academic centres	Number of professors (October 2000)	USPTO patents[a] (1979–2003)	EPO patents[b] (1979–1999)	Number of ISI citations received[c]	Citations per capita
University of Bologna	13	34 (5)	16	5, 319	409
University of Pavia	14	112 (23)	47	4, 656	333
Polytechnic of Milan	18	18 (11)	3	5, 928	329
University Rome Three	12	4 (2)	2	3, 451	288
University of Padova	11	6	3	2, 900	264
University Rome Tor Vergata	17	2	0	4, 027	237
University of Pisa	16	0	0	2, 369	149
Polytechnic of Turin	26	8 (2)	6	3, 057	118
University of Rome, La Sapienza	17	22 (1)	6	1, 830	108
Polytechnic of Bari	10	0	1	721	72
University of Florence	11	4 (1)	3	613	56
University of Genoa	15	0	1	817	55
University of Naples-Federico II	16	0	0	824	52
University of Palermo	15	1	0	507	34
All academic centres	211	211 (45)	88	37, 019	175
University of Lecce single professor[d]	1	25 (12)	6	2, 522	2, 522
University of Catania group	4	13 (2)	7	602	151
Other 23 universities[e]	76	15 (5)	3	14, 025	185
Overall total	292	264 (64)	104	54, 168	186
Number of patenting professors	28[f]	62 (12)	39		

[a] In brackets reference to the patents, if any, for the period 2000–2003.

[b] This column shows Balconi et al. (2003, 2004) data. The correlation coefficient of the two series of patents is 0.985.

[c] *Source*: ISI, Web of Sciences database, citations received in the period 1990–2003 by the publications authored by at least one professor belonging to each university.

[d] Note that the single very productive professor of Lecce de-facto belongs to the Pavia centre, where he graduated and where he still performs research. Owing to the oddities of the Italian system of competitive examinations, it may happen that a professor gets a tenure at a university a thousand miles away from the one that he goes on attending as the centre of his scientific interests. The Lecce professor is thus a case of Italian long distance academic commuter. If we comprised this professor, the number of p.c. citations of the Pavia centre would rise to 479.

[e] Among these 23 universities, the most productive in patenting is the University of Udine, with three patents; then we find a few universities with two patents and the majority with none.

[f] Both EPO and USPTO patents.

assigned to firms and comprising a university professor of electronics among the inventors,[2] and as an indicator of the scientific performance of professors the number of citations received by their papers, in order to capture also the quality of publications (Lach and Shankermann, 2003).

The data collected and presented in the following tables provide a fairly clear picture, consistent with our hypothesis. In particular, Table 1 focuses on whether collaboration with industry is associated with high quality scientific research at the level of the various universities, while Table 2 considers the individual quality level.

More precisely, Table 1 lists the academic centres of electronics in the country – where we define academic centre as any university having at least 10 tenured pro-

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of 2000 and (2) USPTO patent applications from 1979 to the end of 2003. In the case of EPO patents, the shorter period is due to our choice to use the same data as Balconi et al. (2003, 2004), in order to permit comparisons. The list of Italian professors of electronics was supplied by the Italian Ministry of University and Research.

[2] Patents assigned to firms and (co)authored by professors are either yielded in the context of researches funded by firms and performed within university departments or result from the activity of professors as consultants. In the former case, they are part of the output of these researches, which comprises publications, realization of prototypes and training of graduate and undergraduate students working for their final dissertation. A comprehensive discussion of the new evidence of 'university-invented' patents (versus 'university-owned' patents) is offered by Geuna and Nesta (2006). So far the phenomenon has been investigated only with respect to a few European countries: besides Balconi et al. (2003, 2004) for Italy, see Schmoch (2000, 2004) for Germany, Meyer (2003) for Finland, Saragossi et al. (2003) and Du Plessis et al. (2005) for Belgium, Azagra Caro and Llerena (2003) and Carayol (2004) for the Louis Pasteur University of Strasbourg in France.

Table 2
Scientific standing of academic inventors compared to other academics (not inventors)

Age classes	EPO academic inventors		EPO and USPTO academic inventors	
	Citation rank index[a]	Citation share index[b]	Citation rank index[a]	Citation share index[b]
Born up to 1940	1.17	1.81	1.32	2.16
1941–1950	2.61	2.18	2.87	2.48
1951–1960	1.26	1.11	1.80	1.62
1961–1972	1.11	2.19	1.46	2.54

[a] Professors are ranked according to the number of citations received. Since the citation rank index is calculated as: (# of patenting professors/# of all professors)/($\sum$ of the citation ranks of patenting professors/$\sum$ of the citation ranks of all professors), a rank index >1 means a ranking of the group of patenting professors better than average.

[b] The citation share index is the share of citations received by patenting professors (# of citations received by patenting professors/# of citations received by all professors) divided by their numerical share (# of patenting professors/# of all professors). Again, a citation share index >1 means a performance of the group better than average.

fessors officially belonging to the scientific sector of electronics in the year 2000 – exhibiting both the technological output deriving from collaborations with industry and scientific performance. It emerges that collaboration with industry is highly concentrated, since 56% of USPTO patents[3] and 61% of EPO ones authored by tenured academics are produced within two universities, Pavia[4] and Bologna that are also the top-ranking universities (slightly ahead of Milan Polytechnic) in terms of scientific performance.

Note that the number of USPTO patent applications is more than 2.5 times that of EPO ones. This is partly due to the longer period considered, from 1979 until the end of 2003 in the first case and only up to the beginning of 2000 in the second, but over exactly the same time span the amount is still double, while the number of professors involved is 28% higher (50 versus 39). USPTO and EPO patents are in many cases equivalent, namely the same patent extended to the two markets, but a few professors author patents applied to only one of the two areas.

Finally, it can be observed that the diversity of scientific outcomes among Italian universities is remarkable. Moreover, the universities with smaller groups of professors engaged in the field are less technologically oriented than bigger centres, but their average scientific performance is not worse.

Table 2, comparing the scientific performance of individual professors who authored patents with the rest of professors, clearly exhibits that the former are those reporting the largest number of citations. We calculated both the citation rank index and the citation share index (separately for professors of different ages, as the indexes measure outputs cumulated over time). Since the first index is unaffected by the very large number of citations received by few stars, the higher scientific performance of patenting professors appears to be a general characteristic.[5]

Moreover, the academic inventors who signed both EPO and USPTO patents – the 28 professors most engaged in collaborating with industry and producing the most extensively protected inventions – are particularly proficient scientifically as well.[6] Since the latter constitute the core of the epistemic community connecting university and industry in electronics, we decided to focus on them from now on.

5. The teams of co-inventors

The collaboration revealed by patents applied for by firms and authored by professors could derive from either

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[3] In this paper, the ‘patents’ refers to both patents granted and patent applications.

[4] Regarding the University of Pavia, it is worth mentioning that STMicroelectronics opened a laboratory within the university campus and that five other multinational firms recently set up design centres in the area in order to hire the local graduates and to link with professors. At a more strictly scientific level, an analysis of the articles published in the period 1999–2001 in the most important international journal in the field of microelectronic circuits (IEEE Journal of Solid State Circuits) showed that the universities of Pavia and Leuven (Belgium) were the only European ones which contributed significantly. Moreover, the IEEE Solid State Circuits Association’s important ‘Best paper Award’ for the year 2003 was assigned to a paper produced by a research team of the University of Pavia Department of Electronics.

[5] This is consistent with the findings of Breschi et al. (in press), which refer to Italian academic inventors of EPO patents belonging to all disciplinary sectors.

[6] These 28 professors are the authors of patents for which application was made to both patent offices. Since a double application involves additional costs, a high quality of these patents can be assumed (Hinze and Schmoch, 2004), which is another indication of the correlation of the scientific and technological performance of their authors. With regard to their universities of affiliation, besides Pavia (5), we find Rome La Sapienza (5), Bologna (4), Polytechnic of Milan (3), Padua (3), Catania (2) and other six universities (with one professor each).

Table 3
Working position of the co-inventors of the 166 patents signed by the 28 Italian professors of electronics authors of both EPO and USPTO patents

	Number of co-authors	%	Number of signatures on the 166 patents	%
Total university personnel	40	26.8	83	24.0
Other professors[a]	17	11.4	25	7.3
Other university personnel	23	15.4	58	16.8
Final year students	8	5.4	9	2.6
PhD students	11	7.4	43	12.5
Fellows, post-docs	2	1.3	2	0.6
Technicians	2	1.3	4	1.1
Total firm employees	97	65.1	237	68.7
Employees of assignee firms	86	57.7	220	63.8
Employees of other firms	11	7.4	17	4.9
Post-docs of university-industry partnerships	10	6.7	23	6.7
Employees of public research institutes	2	1.3	2	0.6
Total identified collaborators	149	100.0	345	100.0
Non-identified (to be added)	9	–	9	–
Double qualifications (to be subtracted)	7	–	–	–
Total collaborators	151	–	354	–

[a] University professors who had not signed both EPO and USPTO patents or did not belong to the sector of electronics.

research contracted out by firms to universities or the joint activity of academic and industrial researchers. According to our arguments, the latter case should prevail (second hypothesis).

To address this issue, we asked the 28 academic inventors most engaged in collaborations information on the working position of the co-authors of their 166 USPTO patents (phone interviews). Since we were able to identify the working position of 142 over 151 collaborators (94%), we could draw a very precise picture.

Table 3 shows the various categories of collaborators: final year students working for their dissertation, fellows, PhD students, university technicians, employees of the patent holders and of other firms. Double qualifications comprise individuals who changed position during their career, such as PhD students, final year students and post-docs who became firm employees.

The results obtained are of great interest: the contribution of universities to the technological activity of firms increases significantly when one considers all the various categories of university personnel collaborating with professors, but the number of co-authors who are firm employees is even larger (97 as against 68, the original 28 professors included). This confirms our hypothesis about the importance of face-to-face knowledge exchanges between researchers of the two spheres, the academic and the industrial one.

6. The importance of connections between universities and firms for recruiting

In order to verify the importance for firms of linking with qualified universities for recruiting – our third hypothesis – we focused on the effects of the links between firms and the University of Pavia, examining whether the industrial researchers graduated there did exhibit a higher patent productivity than those who graduated in other Italian universities.

To make this step, we had to gather new data. Firstly, we extracted from the USPTO database the complete list of patents signed by the 97 industrial co-inventors of all 28 Italian patenting professors (see Table 3). Then, by resorting to the database of all graduates in Electronic Engineering at the University of Pavia[7] we found out how many of these 97 inventors had graduated there. Thus we could compare the productivity of industrial researchers who graduated in Pavia, with that of the graduates of all other Italian universities, which on the whole are less connected to industry and less proficient.

Table 4 shows the results of our investigation.[8] As expected, not only are Pavia professors the most produc-

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[7] More precisely, we were kindly provided with the database of University of Pavia COR (University Orientation Centre), which has collected the data of local graduates since the inception of the undergraduate course (1975).

[8] The total number of contributions to patents examined is 924, while the share produced by Pavia graduates is 40%.

Table 4
Mean per-capita productivity of the various categories of inventors

Categories of inventors	Mean number of signatures on patents p.c.	Q_1[a]	Q_2[a]	Q_3[a]	Q_4[a]
All professors (28)	7.0	1.8	2	6.3	41
Professors Unipv (5)	18.8	–	–	–	–
Firm employees (97 co-inventors of 28 professors)	9.5	2	6	14	60
Not graduated at Unipv (65)	8.4[b]	1	5	12	60
Graduated or doctored at Unipv (31 + 1)	11.7[b]	2	10	15.3	45

Unipv = University of Pavia.

[a] Q_1, Q_2, Q_3, Q_4 are the quartile values (# of patents signed per-capita).

[b] The difference of the means is significant at the 10% level. When excluding the outlier with 60 patents from the list of inventors not graduated in Pavia, the value of the mean decreases to 7.6 and the level of significance improves to the 5% level.

tive category (especially due to the presence of two stars, who were crucial connectors with industry, co-authoring 41 and 36 patents applied for by firms, respectively), but also Pavia University graduates recruited by companies are significantly more productive than average.

Note that the share of the patents signed by firm employees which is co-authored by professors is almost the same for the two categories (around 25% for both Pavia University graduates and the others). Therefore the productivity levels of Pavia University graduates do not depend on a large number of collaborations with particularly productive professors (a sort of pull effect), but must be attributed to the individual quality of the industrial inventors. Creating the connections useful to access them was certainly very important to industry.

7. Reconstructing the network of co-inventors: methodological notes

In order to examine the network of ties connecting universities with industry in the field of electronics, we used Social Network Analysis (SNA). Our aims were: (i) to analyse the extent to which the characteristics of the ties (such as variety, persistence, direction) vary according to the identity of the connected nodes (academic versus industrial inventors), and (ii) to evaluate the importance of cognitive proximity and personal relationships, taking into consideration the universities of origin of the industrial inventors collaborating with professors. In this case, since we could not get the names of the graduates in Electronics of all Italian Universities, we concentrated our attention on those of the University of Pavia.

In order to identify network participants we selected the 28 Italian professors who authored both USPTO and EPO patents as a starting set of actors. Then, we proceeded to identify their direct and indirect links by the snowballing technique. Usually by this technique an initial set of actors is asked to nominate other participants in the network. The same question is then asked to the latter, and the procedure is further repeated until one decides to stop. Thus the network grows by successive aggregations like a snowball. In our case, instead of asking questions to the initial actors, we obtained information on their ties by analysing the ‘events’ in which they participated with other individuals (i.e. by collecting the names of the inventors co-authoring the various patents) and we went on with the same methodology to identify the ties of the tied actors. More precisely, we took the following steps: (i) we selected the names of the co-inventors of the USPTO patents signed by the 28 professors, namely the latter’s direct collaborators (first circle); (ii) we extracted all patents realised by the direct collaborators from the USPTO database, thereby drawing out the names of the set of collaborators of collaborators of academic inventors (second circle).

We did not expand the network further through the identification of another circle, as these two steps were sufficient to achieve our objectives. Here, we are not interested in the complete structure of the network (in order to know how many steps are required to reach any other member, Newman, 2001), nor are we concerned with nodes distant from academic inventors. As the literature on SNA (see Wasserman and Faust, 1994) demonstrates, interpersonal ties beyond the second step are no longer meaningful.[9]

Note that this methodology does not build the centrality of the starting set of actors into the model. If we

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[9] Importantly, the concept of distance should not be confused with that of strength. With regard to distance, also Granovetter (1973, p. 1372) makes clear that “for some important purposes it may be sufficient to discuss the network made up of ego, his contacts and their contacts”. With regard to the strength of a tie, Granovetter defines it as “a combination of the amount of time, emotional intensity, the intimacy (mutual confiding) and the reciprocal services which characterise the tie” (1973, p. 1361).

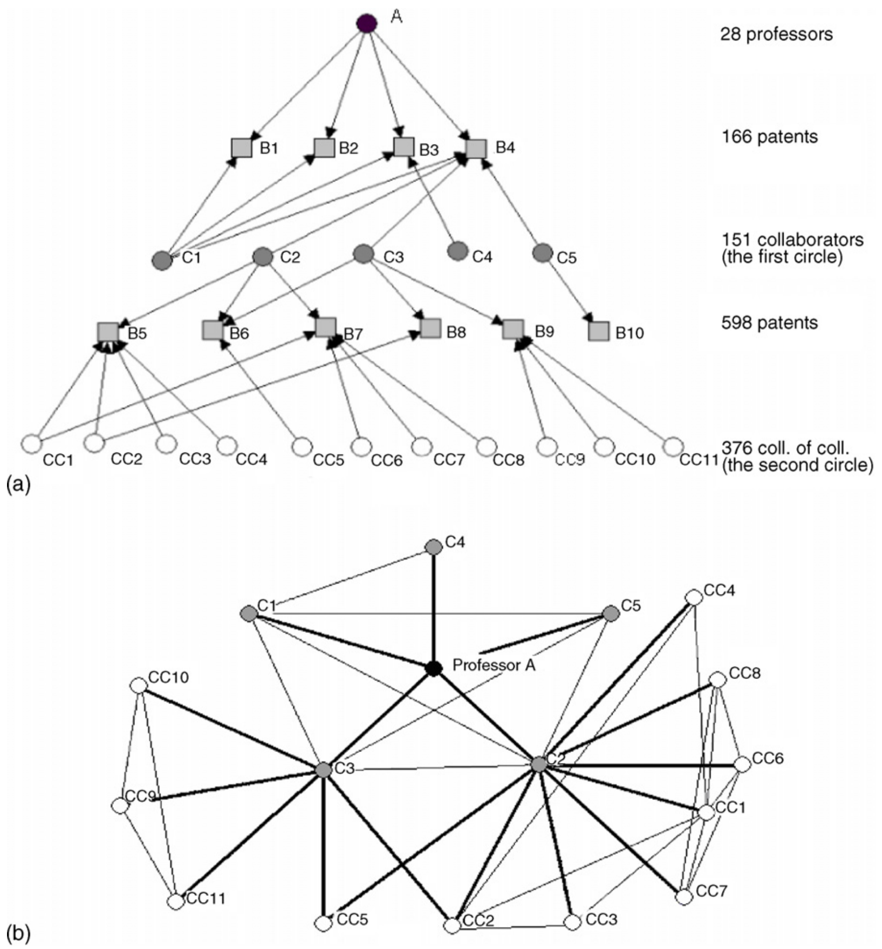

Fig. 2. The two-mode affiliation network (above) and its projection on the inventors (below).

measure centrality very simply in terms of degrees (number of adjacent ties of each node), the starting set of actors and their collaborators are in a symmetric position and fully comparable.

The following figure illustrates the methodology we used. In technical terms, we constructed a two-mode affiliation network that we projected on the inventors, thereby coming up with a one-mode network.

Let us consider, as in Fig. 2(a) (which represents the two-mode affiliation network), a given professor A (at the top) who signed four patents (B1–B4). He is connected directly to the co-inventors (C1–C5) of these patents (first circle of direct ties). If actors C1–C5 co-author other patents in which actor A does not participate, as in the case of patents B5–B10, they belong to other research teams where A is absent. We thus identify the collaborators of collaborators of A (CC1–CC11, who co-author some patents from B5 to B10), who are the actors belonging to the second circle.

The one-mode projection of the network is shown in Fig. 2(b), where the events are skipped and only the ties among the inventors are drawn, both direct and indirect. The paths directly and indirectly linking the inventors to professor A are marked out with thicker lines.

8. Characteristics of the network

Now we present the data that we have analysed (using the UCINET software), in detail.

8.1. Starting group

The 28 academic inventors comprised in the analysis made 195 contributions (signatures) to 166 patents.[10]

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[10] Since some patents are co-authored by more than one professor, the number of contributions exceeds the number of patents signed.

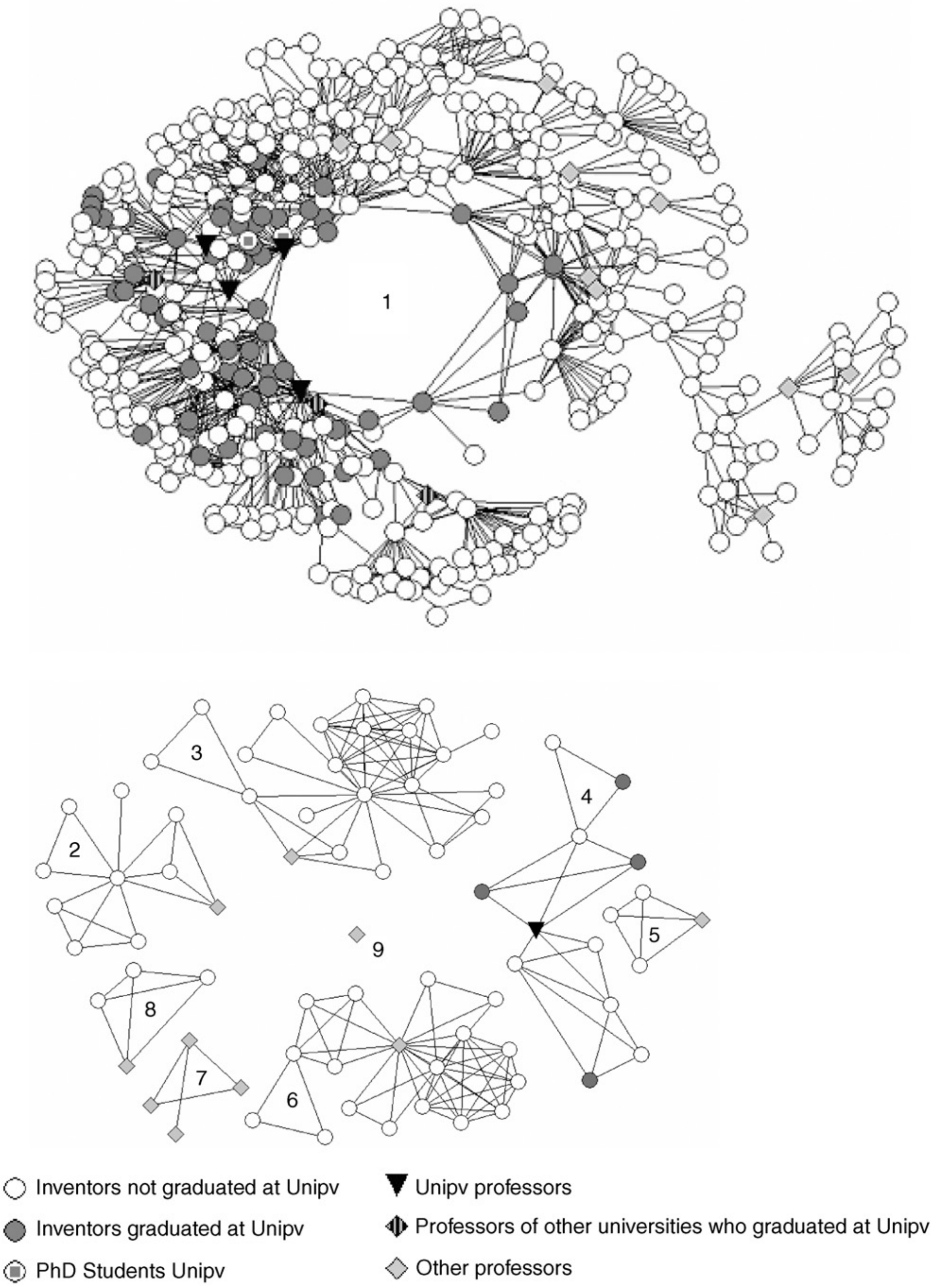

Fig. 3. The components of the network.

Five of them are professors of Pavia University (Unipv) and three belong to other universities but graduated at Pavia.

8.2. *First circle*

The direct collaborators of the starting group are the 151 inventors who were examined in Table 3; they made a total of 1089 contributions to 764 patents (the 166 co-authored by professors included).

8.3. *Second circle*

From the analysis of the 598 patents (events) co-authored by the direct collaborators of professors, we obtained all the acquaintances at distance 2 from the academic inventors. They are 376 inventors, whose total number of contributions to patents we do not know, since we only know that they realized 1193 collaborations with the inventors of the first circle.

8.4. Complete network

Overall, the 764 patents analysed bear 2282 signatures by a set of 555 inventors and generate 3046 relationships (hence we find three co-inventors per patent on average). A 14.6% of the nodes are 81 inventors 'attached' to the University of Pavia, where by 'attached' (or, loosely speaking, member) we mean either tenured professors or inventors educated there (either as graduates or PhDs): (i) eight professors in the starting group (three of whom graduated in Pavia, but moved to another university); (ii) 47 inventors in the first circle (31% of the nodes of the circle); (iii) 26 inventors in the second circle (7%). The contribution by Pavia University members increases to 31% in terms of signatures (707 out of 2282) and to 49.7% in terms of the proportion of patents with a member among the authors (380 out of 764 patents analysed).

With regard to the identity of the assignees, 36 firms are to be credited for 93.5% of the patents (714), while the rest is subdivided among individual authors (3.4%), universities and research institutes (3.1%). A particularly important role is performed by the European semiconductor manufacturer STMicroelectronics (ST), which owns a share of 85% of firms' patents.

8.4.1. The components of the network

In order to describe the structure of a network, it is fundamental to identify the number and size of its components. A component of a graph is a maximal connected subgraph, i.e., each node can reach all other nodes in the subgraph through one or more paths, but has no connections with nodes that are not in the subgraph. Since all the members of a component can communicate with each other either directly or through chains of intermediaries, while isolated nodes are excluded, the model of the components of a graph, their number and size, offers a crucial indication of the opportunities of, and obstacles to communication.

The UCINET software identified nine components in our network of 555 inventors: a very large one, which includes 60% of all professors, and eight much smaller ones, each containing, by construction, at least one professor.

The largest component (component 1, Fig. 3) comprises 479 individuals, 17 of whom are professors, connectors of the academic and the industrial world. In this component the members of Pavia University (professors, graduates and PhDs) are 76 and represent 15.9% of the actors, while the inventors 'reachable' through a path of length ≤2 from the five professors of Pavia University, through direct collaborators (66) or indirect contacts (212), are 278.

Then, we have four medium size and small components with a number of nodes ranging from 22 to 10 (one of which including one Pavia professor and four Pavia graduates), three very small components with only four nodes (one made by professors only) and one isolate.

As to the patent assignees, the main component includes 25 firms in addition to ST, while 12 firms are found in the other components, where ST is absent. Only two firms are split into more than one component, a situation that might indicate poor knowledge management.

In conclusion, the majority of professors participate in a very large component, which offers many occasions for learning, exchanging knowledge and getting new acquaintances in a wide community of inventors including numerous firms, even if a dominant role is performed by a single major industrial player.

8.4.2. The variety and persistency of relationships

An individual with many ties performs an important role in the epistemic community, since he transmits and diffuses uncodified knowledge to many persons, circulating know-how and information among the various research teams in which he is involved. The probability that an inventor has many ties is obviously linked to his productivity. Given the productivity, there is a trade-off for each inventor between the number of different direct ties – the richness and variety of relationships – and their persistency, namely the number of times that he produces inventions by working within the same research groups.

According to SNA, the number of nodes to which an actor is adjacent (its degree), measures his 'centrality' (his position at the heart of the situation, Freeman, 1979).

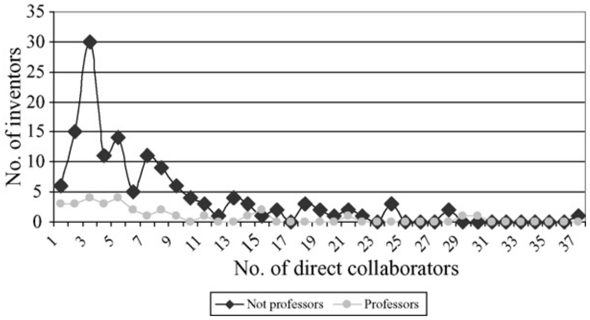

Fig. 4. Distribution of the number of direct collaborators (degree) per inventor.

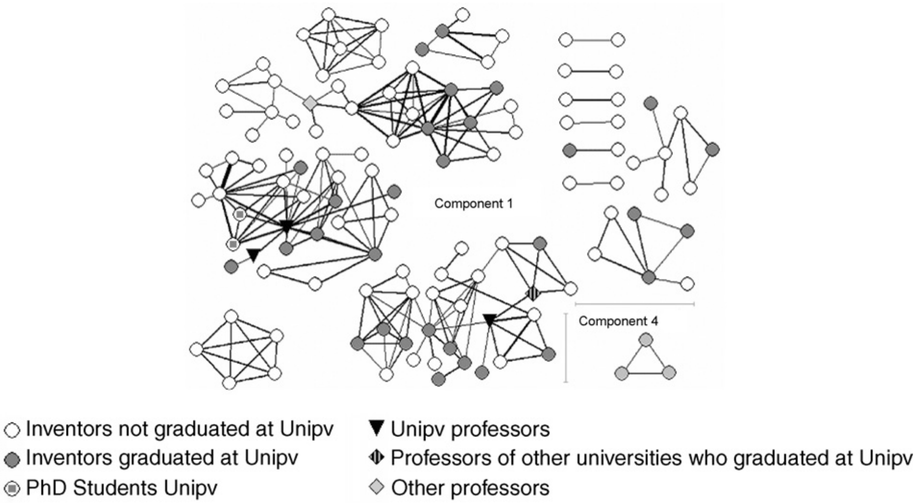

Fig. 5. The network of inventors collaborating at least four times.

As expected, the values of degree centrality we have calculated are closely correlated to those of productivity (the correlation coefficient being 0.834). However, Fig. 4 shows that, unlike professors, the other inventors with few direct collaborators are numerous.

As to the persistency of relationships, it can be represented by a valued graph, where the thickness of the lines depends on the number of ties linking two nodes (in our case, the number of times two inventors co-author patents).

Fig. 5 shows the components of the network of inventors collaborating at least four times.

Overall 15 components emerge, 14 of which originate from the main component and one from component 4. The new picture comprises 121 inventors, 36 of whom (30%) belong to the University of Pavia, whose members, being very productive, are both very central and originators of longstanding relationships. In particular, the four remaining professors are all of Pavia (one of them only having graduated there).

The distribution of all relationships by years of duration is shown in Fig. 6.

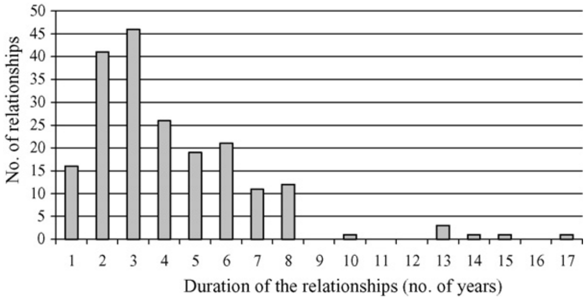

Fig. 6. Distribution of the relationships according to their duration.

8.4.3. The role of professors in training inventors

In order to capture the role of Pavia University professors in training inventors, we analysed all the first patents realised over time by the 179 inventors of whom we know all patents.[11] For every inventor, we searched for the identity of the collaborators who, having already authored a patent, co-authored his first patent, assuming that they had a master's function. Thus, we inserted the data into UCINET asymmetrically in order to get an arrow originating from every 'new-inventor' and directed towards those co-authors who had a previous patenting experience. By counting the numbers of incoming arrows directed to Pavia University professors, other professors and other actors who are not professors, we could compare the role played by these categories in training inventors.

Table 5
In-degree of the various categories of inventors of the first circle

Mean per-capita in-degree	
All professors (28)	4.9[a]
Professors Unipv (5)	10.6
Other professors who graduated at Unipv (3)	7.3
Not professors (151)	3.2[a]

[a] The difference of the means is significant at the 5% level.

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[11] Obviously this required a complete analysis of all the 555 names in our database, since the 'masters' might be located also in the second circle.

Table 6
The preferential ties of professors with former students

Pavia professors	Complete network			Repeated collaboration network			In-degree network		
	Degree	Involving Pavia graduates	%	Degree	Involving Pavia graduates	%	In-degree	Involving Pavia graduates	%
Alfa	30	21	70	15	10	67	24	18	75
Beta	29	15	52	6	4	67	15	12	80
Gamma	14	10	71	2	2	100	10	8	80
Total	73	46	63	23	16	70	49	38	78

Degree = number of direct collaborators.

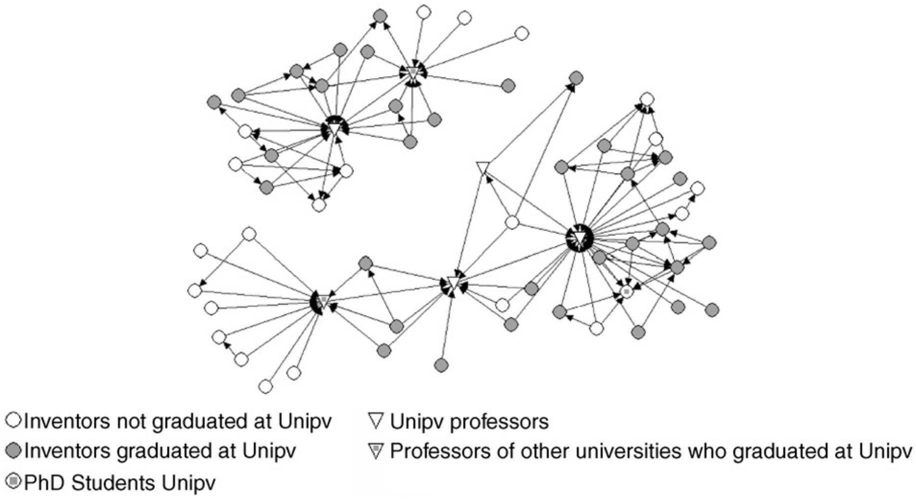

Fig. 7. Networks of master–disciple relationships.

On average, the in-degree of inventors who are not professors is 3.2, that of professors are 4.9 and that of the five Pavia University professors is 10.6 (Table 5). The latter very high value is mainly due to the role of the two stars who, by involving young researchers in their activity of knowledge production, played a particularly important role as educators.

Finally, Fig. 7 shows the master–disciple relationships involving the main masters of Pavia University. One notes, besides three professors, a Pavia University PhD student who also performs a master's function, and the ties of two professors who graduated at Pavia University but then left it: after realising their first patent with Pavia professors, they became important masters themselves. On the whole, Pavia University professors were masters of 53 new inventors, 64% of whom were Pavia University graduates.

Assembling the various pieces of information presented above and concentrating upon the three most prolific professors of Pavia University, we ended up by throwing light on an interesting evidence (Table 6): Pavia University graduates are very important channels linking professors with the outside world. Not only are the direct links of professors with former students particularly important at the beginning of the latter's career (as shown by the in-degrees), but a considerable part of these links persists over time.[12] Our suggestion is that the drivers of these significant ties are both cognitive proximity and personal relationships.

9. Conclusions

This paper focused on the pattern of research in a field of applied research like microelectronics, shedding light on the dynamics of the research and technological

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[12] It is worth noting that while professors tend to link with former students in patenting, the reverse is not true, since we have seen in Section 6 that Pavia University graduates working in industry largely contribute to patents that are not co-authored by professors. Thus industrial researchers are mostly connected to other industrial colleagues, but the ties with their former professors are often significant.

system and on the rationale underlying both the division of labour and the collaboration between universities and industry.

With regards to the dynamics of the system, advances along the technological trajectory of miniaturization of semiconductor devices come first and open up new technological and commercial possibilities. Then, the scientific contributions of microelectronic researchers come into play in order to realise these potentialities. Finally, technological refinements and specific problem-solving activities transform the scientific outputs (comprising new concepts, methodologies and prototypes) into industrial products.

In this context, public funding mainly supports the freedom that allows academics to set their own research agenda to perform explorative, uncertain research. However, since the ultimate goal of research is to provide the foundations for the creation of new artefacts that can work successfully, and that can be produced and sold on the marketplace, academics also need direction from industry. Cooperation with industry is also required because academics' interaction with industrial researchers (with a more technical culture) facilitates problem solving. Conversely, by cooperating with the academy firms receive ideas from professors, enhance the problem-solving capabilities of their researchers and are in a position to effectively recruit new graduates.

On the whole, the research agenda of science is inspired by industry, while to pursue the new avenues that industry considers most promising and that science opens up subsequent technological contributions are required. It would be interesting to compare this pattern with that in other sciences of the artificial, but we conjecture that such a high level of endogeneity of science is the rule rather than the exception.

The results of our empirical investigation are consistent with the research pattern characterising the sciences of the artificial. As expected, proficiency in science is associated with intense collaboration with industry; second, this collaboration is based on face-to-face knowledge exchanges among the members of border-crossing research teams; and third, links with universities allow firms to recruit highly productive individuals. We also discovered that former students recruited by firms constitute in turn the professors' preferential links with firms, due to the cognitive proximity and personal acquaintances.

The patent documents we examined in order to measure the intensity of relationships cover various pieces of knowledge produced within the context of the problem-solving activities carried out by these teams of academics and industrial researchers. While the former are motivated by the typical institutional goal of publishing in scientific journals, firms are not only interested in the main results of the research, but also in codifying and protecting some particular technical findings in order to add new bargaining chips to their portfolio.[13] In this context, academics do not expressly devote any time to producing patents, but papers and patents are complementary outputs, covering different pieces of the same body of knowledge produced[14] – the codified part – while another part remains uncodified, embodied in the individual performers of the craft activity of solving puzzles.

The examination of the co-authors of patent documents allowed us to reconstruct the network of co-inventors, and to identify the role of boundary-spanning scientists. We found that they are at the core of the sectoral epistemic community and, as connectors of relationships, they also play a salient role in the transfer of know-how and tacit knowledge. By including them in collaborative research teams, many industrial researchers learn how to create technological novelties.

In conclusion, the networks of academic and industrial researchers are a fundamental instrument of collaboration between the two worlds and seem quite effective in enhancing productivity in terms of both discoveries and inventions. It would be interesting to know what different logics lead to the different results seen in other sectors in other studies (e.g. Schmoch, 2004). In our opinion, further research seeking to bring to light the specific characteristics of different sectoral research and innovation systems, with a view to comparing them and building (or updating) taxonomies, would be very useful.

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[13] In the field of microelectronics, patents are mainly used for intellectual property exchanges between firms, which permit them to innovate without incurring the risk of infringing someone else's patent (Mazzoleni and Nelson, 1998; Hall and Ham, 1999).

[14] Should researchers deliberately allocate their efforts toward one type of research output at the expense of the other, it is very likely that patents would be owned by the researchers themselves (or the university of affiliation), rather than by firms, since simply co-authoring patents owned by firms is not rewarding for academics.

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