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Research and the practice of publication in industries [1]

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Abstract

Industry publishes relatively few scientific papers. Consequently, it is usually believed that bibliometrics is not very well suited to measure industrial science. The present article tries to assess the usefulness of bibliometrics for measuring industrial scientific activities. 11 814 papers and 84 658 patents originating from 199 multinationals are statistically analyzed in order to understand (1) the importance of industrial publications, (2) the fields of science privileged, (3) the level of science useful to industry, and (4) the science–technology relationships.

1. Introduction

For much of the last 30 years, basic science has been considered by economists as a public good. Indivisibility, uncertainty, and non-appropriability were the three characteristics which were supposed to lead to underinvestment by firms in basic science (Nelson, 1959; Arrow, 1962). Since research is expensive and risky, and since, once available, every firm can enjoy the public good freely, firms have relatively little incentive to do basic research, or so it was argued. As a corollary, firms are recognized not to publish much either. Like basic research, publication by firms is considered more often than not as a by-product of industrial activities only. When, occasionally, firms publish, it is believed that industry publishes mostly applied results, not basic ones.

Price (1965) is probably the one who has gone the furthest in these directions: whereas the chief end product of a scientist's work is the paper (p. 557), the published paper is not, in general, the end product of a worker in a technological subject; he appears to be instead concerned chiefly with the production of an artifact (p. 560). The traditional motivation of the technologist is not to publish, but to produce his artifact or process without disclosing material that may be helpful to his peers and competitors (p. 561). In sum, science is a cumulative activity which is papyrocentric, while technology also cumulates, but in a papyrophobic fashion (p. 561); the scientist wants to write but not read, and the technologist wants to read but not write (p. 562).

Allen (1977) has strongly supported these views with a seminal study of engineers. Allen has shown that the sources of information of engineers is firstly customers, then vendors, and lastly literature: engineers read three times less than scientists (p. 45). They get their information indirectly, through what he call gatekeepers. Others have confirmed these

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conclusions and have quantify the poor record of publications by engineers and industrial scientists (Aloni, 1985; De Smet, 1992).

These assumptions have now come under challenge. Basic science does not consist merely of 'free' information since, to be fully appropriated, the firm must itself perform some research (Mowery, 1983). Cooperative or extramural research, for example, does not function effectively as a substitute for in-house research: knowledge is complex (learning-by-doing), tacit (cannot be completely codified: know-how), cumulative (built on what has already been learned), and firm-specific (Mowery, 1983; Pavitt, 1987; Nelson, 1989).

Recently, Rosenberg (1990) has suggested that part of the benefits be appropriable for the firm to perform some basic research: fundamental research gives first-mover advantages which can be exploited as a barrier to the entry of new firms. In fact, Rosenberg has identified five reasons to explain the presence of basic research in firms: (1) besides conferring a first-mover advantage, (2) or being often unintentional, (3) basic research is a long-term investment, (4) signals one's capabilities (in the federal procurement process for example), and (5) is a ticket of admission to an information network: firms often need to do basic research in order to understand better how and where to conduct research of a more applied nature; basic research is essential for evaluating the outcome of much applied research and for perceiving its possible implications; basic research is indispensable in order to monitor and to evaluate research being conducted elsewhere. The most effective way to remain effectively plugged in to the scientific network is to be a participant in the research process.

We will argue that the same arguments apply to publication by industries. It is usually believed that bibliometrics is not very well suited for industrial output: the conventional wisdom is that industry publishes relatively little. However, Nelson (1990) has argued that firms have incentives to publish: to (1) attract customers, (2) establish legal rights, (3) attract capital, (4) inform suppliers, and (5) gain reputation (attract scientists and engineers; link to the community). Using bibliometrics, we will try to assess the usefulness of publication in industries. We will try to answer four questions:

Table 1
Indicators using bibliometric techniques

Output	Actor	
	University	Industry
Scientific papers	MAIN	
	1.1 do	2.1 do
	1.2 use	2.2 use
	5.0 MIXED	
Patents		MAIN
	3.1 do	4.1 do
	3.2 use	4.2 use

(1) What is the importance of industrial publications?

(2) In which fields of science are industries active?

(3) Which level of science seems the most useful to industry?

(4) With which sciences are specific products associated?

The article divides in two parts. Firstly, we will present our results of a bibliometric analysis of the 199 most innovative firms in the world. Secondly, we will develop a map of the relationship between science and technology.

2. Industrial publications

We have summarized in Table 1 current applications of bibliometrics. The table hypothesized that the main output of universities (academics) is scientific papers (Cell 1.1), whereas the main output of industry is products and processes (here represented as patents) (Cell 4.1). However, sometimes academics can take out patents (Cell 3.1) and industrial researchers can publish scientific papers (Cell 2.1). Sometimes, academics and industrial researchers may work together (Cell 5.0) producing a mixture of papers and patents. Finally, each can refer to the other by means of citations (Cells 1.2, 2.2, 3.2, and 4.2).

To date, bibliometric analysts have mainly studied the outputs from universities and academically related laboratories (Cells 1.1 and 1.2), but the technique has rarely been applied to industrial publications (Cells 2.1 and 2.2). What we do know about industrial publications can be briefly summarized as follows. Bibliometrics has shown that patents cite increasing numbers of scientific papers, and sometimes cite recent papers faster than academics cite themselves (Carpenter et al., 1980; Carpenter, 1983; Narin and Noma, 1985; Narin et al., 1989; Collins and Wyatt, 1988; Van Viannen et al., 1990). It has also indicated that scientific publications by industrial scientists, even if their numbers are still small compared with those from academics (Small and Greenlee, 1977), have increased by 50% in the last decades in the United States (Halperin and Chakrabarti, 1987; Kennedy and Holmfeld, 1989) and Japan (Hicks et al., 1994), and some are highly cited (Narin and Rozek, 1988). This is due mostly to the efforts of high technology industries in the field of aerospace, chemical, drugs, electronics.

It is difficult however to go further than general conclusions with the results of these studies. Their main limitation is that they are performed at a macro level. They usually deal with industrial papers as a whole, sometimes only with particular industries, and rarely do they look at the firm level. Bibliometric studies of industrial publications have tended to be limited in scope. Most have dealt with one technology or one industry at a time, often pharmaceuticals. Exceptions are Small and Greenlee (1977) and Carpenter (1983) who covered all industries. However, these two studies have not apparently been updated since then.

Secondly, they lack any substantive analysis of the specific science–technology relationships involved: few have linked papers with innovations or categories of patents produced by a given firm. The specific relevance of particular sciences to individual technologies remains to be assessed. Which technology builds on which science, and to what extent does one complement the other? What is the nature of the problems on which industrial researchers are working and publishing compared with academics? Are these problems similar or, if they are different, are they convergent or divergent?

Finally, most previous studies have looked only at papers on the one hand, or (citations to science in) patents on the other. Rarely have bibliometrics studies brought together papers and patents to link technology to science.

We have carried out a bibliometric analysis of industrial science which covers all industrial sectors. Our database consists of 11 814 scientific papers published in Science Citation Index (SCI) in 1989 by 199 companies and their affiliates which we have linked to 84658 US patents originating from the same companies. The 199 companies are multinationals which patent most in the United States (see Appendix A). They have been chosen from Science Policy Research Unit (SPRU) database (1969–1986), and they cover 83.1% of US patents granted to 683 multinationals worldwide (Patel and Pavitt, 1989). The 199 companies are representative of R&D funding by industrial sectors as we will see (Section 2.3.).

The multinationals have been classified into 17 industrial sectors. The classification used to that end is the one developed at SPRU and is based on principal product group. The diversity of production will be introduced later in the analysis when patents are analysed according to 32 product groups (Section 3.3.).

We have analyzed only research articles and not any of the twelve other types of documents covered by SCI (e.g. notes, reviews, etc.). This served a positive purpose: it meant that we submitted our data to a more severe test – only primary research papers have been considered. Papers have been classified first into eight scientific fields (clinical medicine, biomedical research, biology, chemistry, physics, earth and space, mathematics, engineering and technology), and second according to whether they are scientific or technological. To this end, a four-level classification developed by F. Narin has been used: applied technology, technological research and engineering, applied scientific research, basic scientific research.

We have selected articles with an address containing the companies' names as they appear in Appendix A. Since these names are those of the patent database, we select in so doing articles originating from the same company as that of the patent database. However, mergers, acquisitions and divestitures are not, as in all bibliometric studies, taken into account unless they changed the name of the company to that of the parent company (only American Telephone and Telegraph (ATT) has been so considered). Although a limitation, this is not particularly troubling. We know, for instance, that firms tend to concentrate

R&D and ownership of patents at the parent company (Rubenstein, 1989). Similarly, one reason why firm publish is to maximize visibility (Nelson, 1990). They do so with appropriate authorship in papers. What we measure with our study is then the visible production of papers from the 199 multinationals.

2.1. Industrial publications' growth

For 1976, Small and Greenlee (1977) have calculated that US industrial papers accounted for 9% of all US SCI papers. Unfortunately, no similar statistics exist for 1989. We can only compare the volume of the scientific production of the 199 firms with the whole scientific production as given by the SCI. The 11 814 industrial papers correspond to about 3% of the SCI research articles. This is almost the same proportion as that of 1980: the precise figures are 2.83% in 1980 and 2.87% in 1989. Our 199 firms thus represents a third of industrial publications.

We can, however, get an idea of the variation in volume of these publications in time. Over the 9-year period between 1980 and 1989, the 199 firms' publications have increased by 21% (while the SCI research articles as a whole have increased by 20%: from 341 964 to 411 176). Although the numbers can obviously vary from year to year, the long term trend is one of growth.

Nevertheless, the increase is less than half that noted by Halperin and Chakrabarti (1987) for US industry as a whole between 1975 and 1983. A possible explanation is that an important share of publications comes from non-patenting firm or from smaller firms. These are not included in our database because they do not patent a lot.

Table 2
Papers by firms (1989)

Papers	Firms
None	39
1–24	97
24–49	14
50–99	16
100–199	18
200–299	7
300–399	2
400–499	3
500–599	1
1000+	2
Total	199

The 199 firms published on average 59 papers in 1989 in journals covered by the SCI. As shown in Table 2, the distribution is highly skewed: only two firms have published more than 1 000 papers. These are IBM (1346) and AT&T (1354). A third one has published a little over 500 (Dupont), three between 400 and 499 (Ciba Geigy, Merck, Hitachi), two between 300 and 399 (Mitsubishi Electric, Siemens) and seven between 200 and 299 (Hoescht, Eli Lilly, Upjohn, Sandoz, Exxon, Toshiba, GM). Most of the firms (68%) published less than 24 papers.

2.2. Industrial publications by countries

By far the most prolific publishing country is USA (Table 3). This is not surprising considering that the US provided 63% of the 199 most highly patenting firms. US-owned firms published 66% of papers in 1989, roughly proportional to the number of US firms in the database. They are followed, some way behind, by the Japanese (14.1%), German (7.9%), and Swiss companies (5.9%). Obviously, our database is skewed in favor of the United States: the contribution of the USA to the world scientific literature is about 35% in 1989, while UK stands at the second place with 8.0%, and Japan at 7.7%.

However, if the United States published the most, it is only in sixth position in terms of the percentage increase in papers between 1980 and 1989. French firms increased their publications by nearly 240%, though from a very low base, Swedish companies by 150%, Japanese by 90%, Dutch by 37%, and German firms by 30%. US firms have increased their production by 12% only. The UK increase stands at 6%. Because of the small number of firms, the growth figures for Canada, Italy and Austria are not statistically significant. Despite the absolute importance of the United States, Swiss firms have the largest output of scientific papers per firm (140), reflecting the domination of drug companies in the Swiss economy, followed by the Netherlands (80), Japan (67), Germany (67), and the USA (62). We now need to explain this picture of countries' publications. To do so, we will look at the firm level.

The French increase is mainly due to one chemical and pharmaceutical firm: Rhone Poulenc in-

Table 3
Papers by country of origin

Country	Firms	Papers 1980	Papers 1989	Increase (%)	Paper/firm (1989)
USA	125	6935	7776	12	62.4
UK	11	305	324	6	29.4
France	9	28	95	239	10.5
Netherlands	3	174	239	37	79.6
Switzerland	5	624	700	12	140.0
FRG	14	715	935	30	66.7
Canada	1	15	14	−7	14.0
Sweden	3	18	45	150	15.0
Japan	25	877	1669	90	66.7
Italy	2	13	11	−16	5.5
Austria	1	1	6	500	6.0
Total	199	9705	11814	21	59.3

Source: data compiled by author from SCI.

creased its output from 8 papers to 84 between 1980 and 1989. A more global approach to R&D probably led the firm to publish increasingly in English journals. Likewise for Switzerland, Ciba Geigy increased its publications from 246 to 403, and Sandoz (pharmaceuticals) from 148 to 289. Switzerland's output in 1989 could have been greater if Brown-Boveri (electronics) has not decreased its publications from 203 to only five, a result due to merger activities. The Netherlands' increase in mainly due to the instruments sector, with Schlumberger jumping from 17 to 72 papers in 1989. It is the electronics sector which explain most of the changes in Germany's output: Siemens increased its publications from 120 to 320. The increase in UK for Beecham (from 80 to 132) and BP (from 13 to 27) is partly offset by Unilever's decrease in food (from 122 to 93 papers).

Japan owes its high position in terms of growth mainly to electronics firms: Hitachi increased its papers from 265 to 457, Toshiba from 66 to 206, Matsushita from 56 to 135, and Nippon Electric from 72 to 189. Other Japanese industries which increased their production are computers, automobiles and metals: Fujitsu (computers) increased its publications from 72 to 126, Toyota (automobiles) increased from 14 to 67, and Nippon Steel (metal) from 34 to 106

Table 4
Papers by industrial sectors

Sector	Firms	Papers 1980	Papers 1989	Increase (%)	Paper/firm (1989)
Chemicals	27	1522	2101	38	77.8
Pharmaceuticals	13	995	1771	77	136.2
Mining	15	525	654	24	43.6
Textiles	3	2	1	−50	0.3
Rubber, plastics	9	55	38	−31	4.2
Forest	3	3	8	160	2.6
Food	13	170	115	−33	8.8
Drink, tobacco	2	6	23	283	11.5
Non-met. minerals	7	89	37	−59	5.2
Metal manuf.	9	94	169	79	18.7
Mechanicals	19	202	161	−21	8.4
Electronics	25	2955	3155	6	126.2
Computers	7	1186	1611	35	230.1
Instruments	10	433	448	3	44.8
Motor vehicles	17	508	566	11	33.2
Aircraft	14	674	576	−15	41.1
Other transport	1	0	0	32	76.0
Multi-industry	5	286	380	21	59.3
Total	199	9705	11814		

Source: data compiled by author from SCI.

papers. These increases reflect the growing presence of Japanese in the world economy and technology.

2.3. Industrial publications by industries

In 1983, Carpenter (1983) noted that the chemical industry was the one which used science the most, as measured by the number of citations to scientific papers in its patents. It was followed by the food, instruments and electronics sectors. Our database shows which industries perform the most science, as measured by the scientific papers produced (Table 4). These are electronics firms which published 26% of papers, followed by chemicals (17%), pharmaceuticals (14%), and computers (13%). These are the industries which are generally regarded as high-technology sectors. This is quite consistent with their position (or ranking) in terms of R&D funding (Appendix B).

The average number of papers per firm is greatest in the case of computers (230), pharmaceuticals (136), and electronics (126). Instruments (45), mining (43), aircraft (41), and automobiles (33), however, form a second group of scientifically quite prolific industries.

Notwithstanding industries for which the total number of papers is very small, the greatest increases between 1980 and 1989 occurred in metals (79%), pharmaceuticals (77%), chemicals (38%), and computers (35%). Again, a second group of industries, usually not regarded as being science-based, appears: besides metals, already identified above, these are mining (including petroleum) with a 24% increase and automobiles (up 11%). This is in contrast to the data on R&D funding: the metals industry has decreased its R&D investment between 1983 and 1989, while mining has slightly increased its R&D expenditure. We will now try to find explanations for this with an analysis at the firm level.

Only 15 chemical firms, out of a total of 27, increased their production of scientific papers between 1980 and 1989. The most important increases are for Dow Chemicals (up from 97 to 146), Dupont (from 203 to 566), Rhone Poulenc (from 9 to 84), and Ciba Geigy (from 246 to 402). Another 11 firms decreased their production. Among these are Union Carbide (down from 108 to 44), BASF (down from 108 to 77), and Bayer (from 193 to 152).

Among pharmaceuticals companies, the increases are more common. Only one firm decreased its publications (American Hospital), and two others remained constant (Bristol and American Home Product). Ten firms out of 13 increased their output of scientific papers. Among these are Eli Lilly (up from 113 to 215), Merck (from 200 to 440), Schering (from 112 to 172), Pfizer (from 84 to 146), Upjohn (from 174 to 276), Beecham (from 80 to 132), Sandoz (from 148 to 289), and Boehringer (from 29 to 64). This reflects the growing importance of basic research for the industry as seen in Section 2.

Eight firms in the mining and petroleum industry, out of a total of 15, increased their scientific production, but only Exxon did so appreciably (from 212 to 294).

Only two firms in the food industry, out of a total of 13, have increased their production of papers. Six firms did not publish any papers in 1989. The biggest decreases occurred with Nestle (down from 26 to 4) and to a lesser extent Unilever (from 122 to 98). The same pattern of overall decline occurs in the non-metallic industry, where only one firm has slightly increased its output of scientific papers. As we have noted earlier, these are industries which do not invest much in R&D.

In the metals industry, Thyssen and Nippon Steel exhibited the biggest increases: from 8 to 41 papers in the case of Thyssen, and from 34 to 106 for Nippon Steel. US Steel, however, decreased its publications from 20 to zero. As for the mechanical industry, the US firm, Hughes, decreased its scientific production slightly from 149 to 122. No less than 11 of the 19 mechanical firms did not publish any papers in 1989. In fact, mechanical industry is well known not to perform much basic science (Carpenter, 1983).

The increases in the electronics sector are mainly dominated by non-US firms, particularly Japanese firms. Siemens of Germany increased its number of papers from 120 to 320. Hitachi increased its total from 265 to 457, Toshiba from 66 to 206 and Matsushita from 56 to 135. The only important US increase occurred with Texas Instruments (from 73 to 122).

Some big US electronics corporations decreased their scientific production. This is the case for ATT (down from 1421 to 1354), RCA (from 188 to 16), and Westinghouse (from 215 to 138). Computers firms stand apart from this trend. IBM increased its publications from 977 to 1346, and Fujitsu from 72 to 126. Only Sperry showed a big decrease (from 37 to two papers).

The standing of the instruments industry is strongly influenced by Xerox which fell from 304 to 153 scientific papers. Besides this decrease, significant improvements are noticeable with Kodak (up from 94 to 155), Schlumberger (from 17 to 72), and two Japanese firms, Ricoh (up from 1 to 11) and Canon (from zero to 26).

In the automobiles industry, only the Japanese firm Toyota appreciably increased its output of papers (from 14 to 67). GM decreased its total from 254 to 226, and Fiat from 13 to only four. Ford increased only slightly (from 106 to 118), while Daimler-Benz, Honda and Nissan also increased slightly, but still published less than 15 papers a year in the decade. As for the mechanical industry, the automobiles sector has never been heavily involved in basic research, and is even.

Finally, the aircraft industry offers a mixed picture. Some big firms have decreased their publications. Grunman dropped from 42 to 24, Rockwell from 192 to 119, Boeing from 73 to 59, Lockheed from 134 to 103, and Rolls Royce from nine to two. Some others have slightly increased their production. This is the case of Northop (up from 32 to 49), Martin Marietta (from 44 to 58), McDonell Douglas (from 58 to 64) and General Dynamics (from 14 to 26). Three other firms deserve mention because they remained approximately constant: United Technologies (57 papers in 1980 and 55 in 1989), British Aerospace (12 and 11 papers respectively), and Aerospatiale (one paper in both 1980 and 1989).

Overall, high-technology industries (chemicals, pharmaceuticals, electronics) publish most papers. However, the picture is a little more complex than that. One industry renowned as a high-tech sector (aerospace) does not publish as much as the others.

Table 5
Scientific disciplines by industrial sectors (1989)

Sector	Papers	CM	BR	BI	CH	PH	ES	ET	MA	OT
Chemicals	2101	551	264	133	485	150	47	183	2	7
Pharmaceuticals	1771	945	371	31	228	2	3	9	2	
Mining	654	18	36	17	169	116	86	96	7	5
Textiles	1				1					
Rubber, plastics	38			2	20	3		10		1
Forest	8	1						6		
Food	115	24	26	6	28	4		3		
Beverage, tabacco	23	1	2	2	10		2			1
Non-met. minerals	37	1	2	1	3	7	1	8		
Metal manuf.	169	1	2		7	19	2	75		
Mechanicals	161	14	1	2	6	66	1	46		
Electronics	3155	83	60	30	287	1519	36	829	48	2
Computers	1611	51	60	1	1	639	4	277	14	1
Instruments	448	7	15	1	85	215	21	38	1	
Motor vehicles	566	34	16	2	79	143	34	144	5	1
Aircraft	576	15	13	12	40	179	44	159	7	1
Transport (others)	0									
Multi-industry	380	16	61	7	54	82	5	81	2	
Total	11814	1762	929	247	1503	3144	286	1964	88	21

CM, clinical medicine; BR, biomedical research; BI, biology; CH, chemistry; PH, physics; ES, earth and space; ET, engineering and technology; MA, mathematics; OT, other.
Source: Data compiled by author from SCI.

Moreover, two industries which are not generally regarded as high-tech industries publish as much as aerospace: these are automobiles and instruments.

The greatest increases in scientific publications between 1980 and 1989 (for industries with more than 100 papers) have also occurred in high-technology industries. One exception, however, is the metal industry which increased its output of papers by 79%. The greatest decreases between 1980 and 1989 have occurred in industries which do not publish very much. There is one exception again, the aircraft industry. In summary, we observe a more complex picture than the usual dichotomy of science-based industry, on the one hand, and other industries, on the other hand. Some new industries are entering the field of scientific publication, while others are leaving the field.

2.4. Industrial publications by disciplines

If we now turn to the distribution of papers by disciplines, we see that the scientific field in which industries publish most (Table 5) is physics (31%). Other fields appear in the following order: engineering (19%), clinical medicine (17%), chemistry (15%), biomedical research (9.3%), earth and space (2.8%), biology (2.4%), and mathematics (0.8%). This is an important result in the following sense.

This distribution of fields resembles quite closely the distribution found in bibliometric studies by Computer Horizon Inc. (CHI) in the 1980s when they examined the disciplines represented by citations to the scientific literature in patents. If we compare Narin and Olivastro's (1992) study with ours, we observe a similar distribution for all industries combined except for two disciplines which appear in reversed order: physics and chemistry, the latter appearing first in Narin and Olivastro's study. How can we explain the results?

The importance of life science, and particularly chemistry for industry in now well established. Small et al. (1985) showed that life sciences (clinical medicine, biomedical research, and biology) constitute the main core of the scientific production for companies; they also represent 47% of citations. Small and Greenlee found that industry publishes 60% of its papers in the life sciences.

It is somewhat surprising, then, to find that, contrary to previous studies, our analysis points to the apparent dominance of physics. Our data suggest that only 29% of the papers come under life sciences, compared with 34% for physical sciences (physics and geoscience) and 19% for engineering and technology.

These results are not necessarily in conflict, however. Firstly, if we compare the industrial papers in our study with the volume of scientific production as a whole, we observe that industry publishes twice as many papers in physics (as a proportion of the total), and three times the relative number in engineering and technology. It publishes half the number in clinical medicine and biomedical research, but about the same amount in chemistry. Our data point to the specialization of industrial science in physics and engineering. Alternatively, they could indicate that this specialization is more pronounced in the case of the most patenting firms, since our data are based on these firms only.

Secondly, and more importantly, the results could also mean that, while physics is perhaps no more useful to industry than chemistry, it is used in a different way. We need to remind ourselves of the distinction that we made earlier regarding science in industry (Table 1): industry can use already available science (science produced outside industry) and cite it; or it can do (new) science itself. Narin's data show that industry cites (three times) more chemistry (39%) than physics (13%), while our study shows that industry does more physics (31%) than chemistry (15%). The two disciplines are probably complementary assets.

This could reflect the different degree of appliedness of research in each field. The importance of biotechnology in chemistry, for example, where basic research is mostly performed in universities and where large firms have entered the field lately, versus the more applied nature of physics performed in industry, particularly nuclear physics closely related to engineering applications. Consequently, industry develops its own expertise in physics, but relies more on universities for chemistry.

2.5. Industrial publications by level of research

Using Narin's classification of journals, we tried to quantify the relative importance of type of knowledge for industries. For each firm, we have classified papers according to the level of research of the journals in which they appear. The four levels are applied technology (Level 1), technological research and engineering (Level 2), applied scientific research (Level 3), and basic scientific research (Level 4). For biomedical areas, the levels are as follows: clinical observation (Level 1), clinical mix (Level 2), clinical investigation (Level 3), and basic biomedical research (Level 4).

We have interpreted the four categories according to the following distinction: on the one hand, we have papers dealing with science (Levels 3 and 4); on the other hand we have papers concerned with technology (Levels 1 and 2). While our classification uses the standard categories of the linear model of innovation, it represents two improvements here. First, levels of research, because they are defined by the journals in which the article appeared, reflect the nature of the actors' output, not the motives (curiosity or practical) of the researchers. Second, technology journals are directly identified and distinguished from science journals. Let us now turn to the results.

Most studies to date have judged industrial research in the light of university research. Consequently, they point to the low level of basic scientific research performed in industries. Our data could be interpreted in the same way: only 29% of the papers in our database can be classified as basic scientific research and 41% fall into the applied science category (see Table 6). This is less than what Small and Greenlee found for large firms in the United States several years earlier (around 40%).

Table 6
Level of research by fields (1989)

	Technology		Science	
	Applied	Basic	Applied	Basic
Clinical medicine	9.7	25.2	53.7	11.2
Biomedical research	0.1	1.0	4.6	94.2
Biology	2.3	30.4	41.4	25.7
Chemistry	0.2	14.7	46.3	38.5
Physics	0.6	3.3	65.0	30.9
Geoscience	2.3	38.4	24.4	34.6
Engineering	38.5	52.2	8.5	0.6
Mathematics		44.5	31.5	23.9
Total	9.3	20.2	41.4	28.9

Source: data compiled by author from SCI.

Table 7
Level of research by industry

	Technology		Science	
	Applied	Basic	Applied	Basic
Chemicals	8.8	15.1	38.9	36.9
Pharmaceuticals	5.5	15.9	37.2	41.1
Mining	10.7	17.5	30.8	40.9
Textiles				
Plastics	27.7	44.4	16.6	11.1
Forest	85.7	14.2		
Food	2.0	19.7	43.7	34.3
Beverage		11.1	77.7	11.1
Non-met. minerals	8.3	37.5	25.0	29.1
Metal	27.8	35.4	26.5	10.1
Mechanical	21.8	21.8	45.2	10.9
Electronics	10.1	23.4	43.1	23.2
Computers	8.3	22.8	48.2	20.5
Instruments	4.4	16.1	48.0	31.3
Motor	19.9	23.8	41.7	14.5
Aircraft	9.6	26.3	46.2	17.7
Transport				
Multi-industry				
Total	9.3	20.2	41.4	28.9

Source: data compiled by author from SCI.

However, we can interpret the numbers differently. We should note, firstly, that from the point of view of industry, the level of basic science is not necessarily low since the purpose of industries is not basic research per se, but, as Irvine and Martin (1984) have suggested, research which should ultimately be useful to industry (strategic research). Seen in this way, neither basic nor applied categories are exclusive: that is, basic research is not exclusive to universities, and applied research is not exclusive to industry. They overlap.

Secondly, when we separate knowledge into its science and technology components, the total production of scientific knowledge in industry amounts to 70% of all the papers. Obviously, most technological knowledge is related to engineering. However, biology, geoscience, and mathematics also have an important technological component.

Six industries have a science component greater than the mean of industries (Table 7). These are beverage (88.8), instruments (79.3), pharmaceuticals

(78.3), food (78.0), chemicals (75.8), and mining (71.7). Two of these are from the group of highly publishing industries (pharmaceuticals, chemicals), two from the medium publishing industries (instruments, mining), and the others from the low publishing industries (food, beverage). Computers (68.7) and electronics (66.3) falls slightly behind the mean.

Finally, we have computed the mean level of articles for each industry. To articles of Level 1, we have attributed a value of 1; to articles of Levels 2, 3, and 4, we have attributed a value of 2, 3, and 4 respectively. The mean value represents the level of 'basicness' of research performed in one industry.

The results are as follow. The mean level for all industries is 2.8. Industries which are the most basic are pharmaceuticals (3.1), followed by chemicals (3.0), mining (3.0), instruments (3.0), food (3.0), and beverage (2.9). Not far from the mean, but below it, are computers (2.7), aircraft (2.7), electronics (2.7), non-metallic minerals (2.7), then motor (2.5) and mechanical (2.4). Nearer the applied end are metal (2.1), plastics (2.1), and forest (1.1).

The mean level we found for pharmaceuticals is similar to the one calculated by Narin and Rozek (1988), i.e. 3.1. Interesting results are the good performance of instruments relative to science (3.0), but more surprising is the position of electronics below the mean (2.7). Finally, the mean level of metals (2.1) implies that the increasingly publishing behavior of that industry (see Section 3), particularly in Japan, is mostly due to applied science.

Overall, the publications of industry is mostly science than technology, and mostly applied science. The science component is mostly evident in high-technology industries, but also in some others industries. The science component is quite similar to the one found by Small and Greenlee (26%), but the applied component differs (25%). This probably

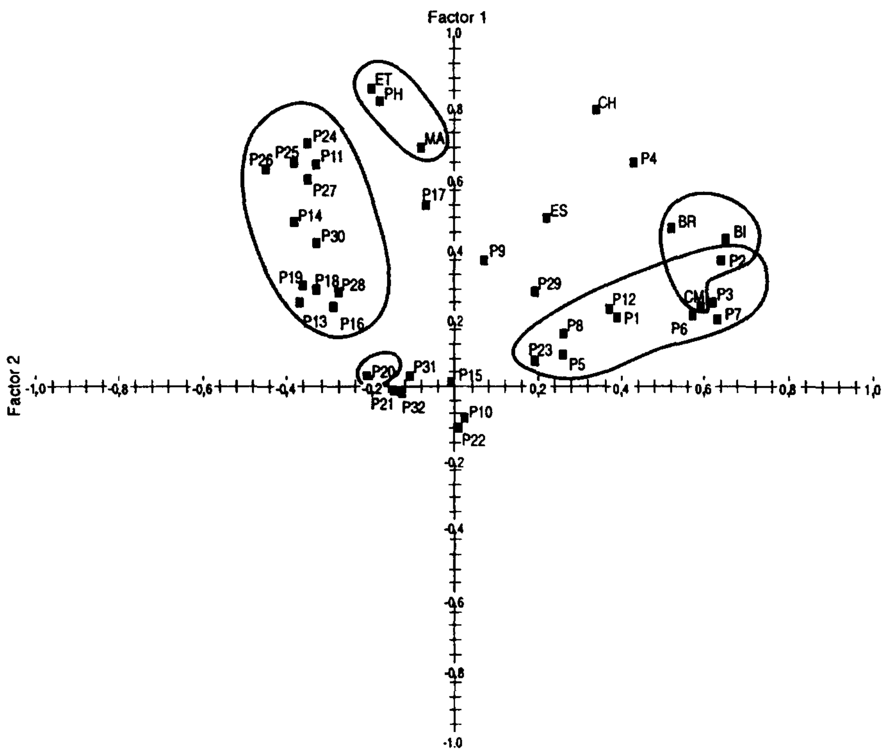

Fig. 1. Grouping of papers and patents.

means that our multinationals do research of a more applied nature than the other firms.

3. Mapping science–technology relationships

There have apparently been no studies which have linked all scientific disciplines with technological fields. The objective of the present section is to link both science and technology to different industrial sectors. Two statistical techniques has been used to this end. Firstly, factor analyses have been performed at the industry level on both papers and patents. The details of patents, classified into 32 product groups, for each of the 17 industries appear in Appendix C. Secondly, in order to better understand the groupings that the factor analyses has give, we have computed correlations between papers and patents to see the strength of the relations between the two.

3.1. Groupings of sciences and patents

Fig. 1 presents the result of a factor analysis performed for each industry. The volume and distribution of papers by discipline has been correlated with the volume of patents by product group. Factor 1 correspond to a physical science-based dimension of science while Factor 2 corresponds to a life science-based dimension. Three groups of papers constitute the core of industrial knowledge. [2] Two of them are composed of highly interrelated papers, and papers which define the central research interest of industry: life sciences (clinical medicine, biomedical research, biology) and physical sciences (physics, engineering, mathematics). The other group of papers is more isolated and composed of earth and space sciences (resembling physical sciences in term of their distribution in industries) and chemistry (between physical sciences and life sciences).

This pattern of industrial science corresponds roughly to the mapping of science (co-citations) in general (Small et al., 1985). Although the distribution in volume of disciplines is different, the mapping puts biomedical sciences on one side, physical on the other, and chemistry in between.

The horizontal axis of the figure (Factor 2) can be seen as a dimension corresponding to whether industries are life-science based or not. Factor 2 best explains life science disciplines: the correlation with clinical medicine is 0.77, with biomedical research 0.62, and with biology 0.54. Other coefficients of Factor 2 are uncorrelated with papers, or negatively correlated. The vertical axis (Factor 1) represents the physical science-based dimension of industrial science. The correlation coefficient between Factor 1 and physics is 0.83, with engineering-technology 0.83, mathematics 0.80. It also correlates with chemistry (0.92). The extremely high value of chemistry confirms its central position, not only in the life sciences, as Narin has shown with citations, but also in physical sciences. The two-dimensional distribution of papers distinguishes between different industries reasonably well: 72% of the distribution is explained by the two factors.

Patents does not explain as much variance: only 29% of the variance is explained by the first two factors. However, Factor 2 explains quite well the covariance in chemicals patents (organic chemicals, 0.78; chemical processes, 0.77; chemical apparatus, 0.65), while Factor 1 still explains a physical dimension (metal, 0.74; industrial equipment, 0.78; telecommunication, 0.67; semiconductors, 0.66; electronics, 0.83).

Despite the inadequacy of the two main factors to explain most of the patenting activity, patents group quite well into three broad classes:

(1) information–telecommunication (Classes 24, 25, 27, and 28), appearing together with equipment and machinery (Classes 11, 13, 16, and 30) and with energy patents (Classes 18, 19, 26);

(2) transport (Classes 20, 21, and 22);

(3) chemicals and pharmaceuticals (Classes 1 to 7, and 12).

Again, patents group along the same dimension as science: life patents together in Quadrant 1, and physical patents together in Quadrant 2. Groups 1 and 2 of patents are related to physical sciences, while Group 3 is related to life sciences.

Overall, two main results appear. Firstly, papers discriminate better between industries than do patents, even better than the two together. This prob-

[2] The codes for Fig. 1 appear in Appendix C.

ably represents the specialization of industry in science. Of course, one could argue that the number of variables is great (32 classes of patents) and, for that reason, is probably partly responsible for the poor overall contribution of the two factors in explaining the patent distribution.

Secondly, for both papers and patents, the physics dimension is the one which best explains the variance. This could be a consequence of the larger number of physical-based industries (as opposed to life science-based) included in this study, but it also is in line with, and gives support to, the specialization of industry in physical sciences.

3.2. Papers and patents linkages

In order to better understand the relations between papers and patents, we have then computed correlations between the two at the category level instead of the volume. Three main separate groups can be observed. The first group of correlated papers is composed of clinical medicine and biomedical research. Clinical medicine and biomedical research, accounting together for 27% of papers, are highly correlated between themselves ($R = 0.98$), and related to drug patents ($R = 0.98$ and 0.97 respectively). Drugs account for 5.1% of patents.

A second, more complex group is composed of chemistry and biology. Chemistry is highly correlated to biology (0.89). This group yields in total 17% of papers, and is related to eight categories of patents. These patents, mostly chemical, account for 28% of all patents. Correlations occur through chemical processes, a category which is itself correlated with two groups of patents: applied chemicals (organic and agricultural) and energy (mining, oil).

Of the two sciences composing this group, chemistry is obviously the most important in term of volume of publications and patents, but biology is the one which has the greater number of links with patents: chemistry is related to organic chemicals patents (0.84) and to chemical processes patents (0.85), whereas biology, probably via microorganisms tests, is related to chemical processes (0.87), agricultural chemicals (0.95), organic chemicals (0.98), and bleaching agents patents (0.96).

The third and last block is the most complex. Composed of physics, engineering, and mathematics which make up 52% of papers, the volume of papers in the three sciences is highly correlated: physics is closely correlated with engineering-technology (0.97) and with mathematics (0.97); mathematics is equally correlated with engineering-technology (0.97). All three sciences are highly correlated with two groups of patents: first, with a class of patents (34% of all patents) highly correlated among themselves – information/communication patents (telecommunication, semiconductors, electricity, computers, audiovisual) and instruments; secondly, with a class of patents (4.7% of all patents), itself correlated with the first, and composed of processes (metal) and equipment (industrial and nuclear).

Apart from these three main groups, other links are weak: geophysics papers are correlated only with apparatus for chemicals, and 28% of all patents are not highly correlated with any specific science.

What emerges, in the overall picture, is a pattern quite closely resembling Pavitt's (1984) results concerning science-based industries, especially if we leave aside other industries as non-science-based [3]: in particular, chemicals, pharmaceuticals, electronics, and computers patents are highly related to science and to specific sciences. However, the pattern differs in some respects. More patents appear to correlate with science, especially in the instruments, apparatus, and processes sectors. According to Pavitt, industries responsible for these products are classified as scale-intensive industries, not as science-based industries.

Pavitt's taxonomy is based on the origins of products, whether these are internal or external to the firm. This allows him to distinguish between goods and processes, the latter being treated as intermediary goods (Pavitt, 1984; Robson et al., 1988; Archibugi et al., 1991): processes are products often produced outside a given firm and used as a means to produce its own products. However, this distinction is of little use here because it deals with commercial flows of artifacts. Since processes (as well as products) can rely on scientific and technological knowledge, commercial flows do not necessarily tell us anything about science and technology flows.

[3] Because Pavitt defines chemicals as including mining, the latter is already considered as science-based in his taxonomy.

This is exactly the lesson to be drawn from the history of instruments: instruments are often first developed in the course of basic research, refined and scaled-up in industry, then returned as goods to universities (Rosenberg, 1990).

3.3. Specialization and diversification

How can we integrate 'new' science-based patents, and the industries responsible for them, into Pavitt's taxonomy? We have organized the relation between papers and patents into each industry according to an input–output model. We have proceeded in four steps.

Step One: The percentage distribution of papers and patents has been calculated for each industry.

Step Two: We have kept, for reasons of statistical representativeness and for better visual representation, only the most prolific industries in science, i.e. those for which the number of papers is equal to or greater than 100 in 1989.

Step Three: We have organized the data according to an input–output model. We have assumed that papers correspond to inputs (publication reflects the science and technology used in industry), and patents to outputs (artifacts). Industry uses knowledge as an input to produce artifacts as an output.

We do not assume here that the 1989 papers served to produce specifically the 1986–1989 patents. Papers are used here merely as indicators of useful knowledge (scientific and technological) for industry, and patents as types or categories of artifacts produced concurrently with this knowledge.

Step Four: Finally, we have mapped the relations between inputs and outputs. Fig. 2 maps two types of flows: major flows of papers and patents are shown as solid lines, and secondary flows as dotted lines. Major flows are defined as papers or patents that represent more than 50% of the total in an industry, while secondary flows correspond to those which represent about a third of the total only.

The map is composed of three kinds of elements:

1. The actors: the industries responsible for inputs (papers) and outputs (patents), represented as boxes. The eleven industries mapped are: pharmaceuticals, chemicals, food, mining, instruments, electronics,

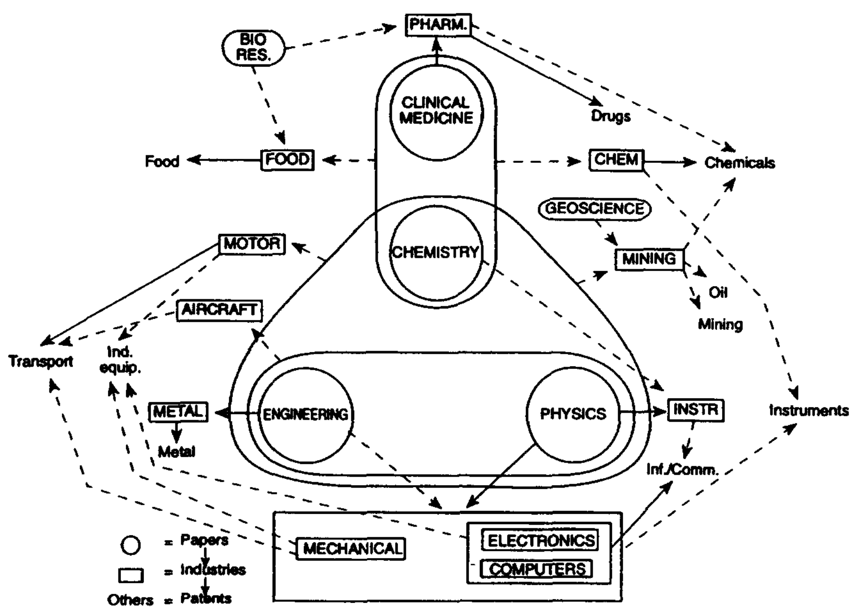

Fig. 2. Mapping of the flows between knowledge and artifacts.

computers, mechanical, metal, aircraft, and automobiles (motor vehicles).

2. The inputs: the scientific knowledge useful to industries and in which they publish, represented here as circles. The four main disciplines are clinical medicine, chemistry, physics, and engineering.

3. The outputs: the patents, organized around seven broad categories: chemicals (inorganic, organic, agricultural, processes, and apparatus), metal (processes, equipment, miscellaneous), industrial equipment (general industrial equipment – electrical and non-electrical, specialized industrial equipment), transport (road vehicles, aircraft, other transport), information-communication and electronics (telecommunications, semiconductors, computers, image and sound, and photography), drugs, and instruments.

Three broad conclusions can be derived from the map. Firstly, industries are not dispersed in their scientific efforts. Two types of industries appear on the basis of the sciences they carry out: half of the industries rely on one main core field of knowledge (solid lines). These fields are clinical medicine in the pharmaceuticals sector (59.3%), engineering in the metal sector (70.7%), and physics in computers (60.9%), in instruments (56.1%), in electronics (52.4%), and in the mechanical sector (48.5%). Other industries use a combination of fields, only the biggest ones being identified graphically (using dotted lines).

Industries active in physical sciences (physics, engineering, geoscience) do not publish many papers in the life sciences (clinical medicine, biomedical research, biology), and vice-versa. Chemistry, however, is the discipline that is present within both groups of sciences in industry: chemistry contributes as a main science in food (30.7%) and mining (30.7%), as a secondary science in chemicals (26.6%), and as an important resource to instruments (22.1%) and motor (17.2%).

Secondly, industries are relatively specialized in their patents. Industries associated with life sciences patent in life science classes of patents, whereas those specialized in physical sciences patent in physical classes. Half of the industries have high concentration ratios of patents (solid lines): pharmaceuticals companies in drugs patents (61.1%), food companies in food patents (82.3%), metal companies in metal patents (69.2%), computers in patents related to information-communication technology (73.9%), and chemicals companies in chemical products and processes patents (61.9%).

We can also see that most of the patent classes are mainly (more than 50%) accounted for by one industry: organic chemicals patents (72.3%) and agricultural chemicals patents (84.1%) by the chemical industry; drugs (55.3%) by pharmaceuticals companies; oils (79.0%) and mining (58.9%) by the mining industry; food patents (63.9%) by the food industry; general industrial equipment (63.9%), telecommunication (74.8%), semiconductors (69.4%), computers (60.3%) and image-sound patents (81.7%) by the electronic industry; road vehicles patents (83.4%) by the motor industry; and aircraft patents (73.1%) by the aircraft industry.

Thirdly, and finally, the pattern of concentration of papers and patents together varies according to industries (see Fig. 3). Pharmaceuticals, computers

		Knowledge		
		Concentrated		Dispersed
Artifacts	Concentrated	**PHARMACEUTICALS** **COMPUTERS** METALS		FOOD **CHEMICALS**
				MOTOR
	Dispersed		INSTRUMENTS **ELECTRONICS** MECHANICALS	AIRCRAFT MINING

Fig. 3. Concentration of industries according to papers and patents.

and metals are industries which are concentrated both in papers and in patents (around two thirds of papers and of patents are in one category only). The instruments, electronics and mechanical sectors are also relatively concentrated in papers (around 50% of papers fall in only one category), but much less concentrated in patents (about one third or less in only one category). At the opposite extreme, the food, chemicals, and to a lesser extent motor vehicles sectors, are concentrated in patents, but less concentrated in sciences. Aircraft and mining are dispersed in terms of both papers and patents.

Overall, our results suggest that we do in fact have artifacts specifically associated with a given knowledge, as the applied science thesis leads us to believe. However, we also have some industries relying on a larger range of science to produce only a few categories of patents. In addition, we have some industries relying on one main science to produce several categories of patents. Industries are not necessarily dependent on a given area of scientific knowledge. Besides the traditional science-based industries, half of which are concentrated in one core area of scientific knowledge (pharmaceuticals and computers), the other half dispersed (electronics, chemicals), other industries, driven both by competition and by their market relations, are trying to exploit a wider range of sciences.

4. Conclusions

Bibliometric analysis of industrial science are comparatively rare. What the few studies carried out have shown, however, is that scientific research is increasingly present in industry: the production of scientific articles by industry, despite its small volume, has increased by approximately 50% in the last decade. At the same time, patent citations to science have increased by 300%. The impact of industrial science has been little studied however: there have been few bibliometric studies of citations to industrial papers. The impact of science in general on industry is rather better understood: citations in patents are often to basic science and are as recent as academics' citations – sometimes even more up to date, at least in fields related to life sciences. In short, science seems to be increasingly related to technology, as Narin has suggested. Industry is producing more and more science, as reflected in the volume of publication, and, at the same time, it is using more basic research as shown by their citations.

Industrial publication of the 199 multinationals are represented by the 199 firms which produce the most patents in the US, represents around 3% of the total number of papers in the SCI. This percentage has increased by one fifth between 1980 and 1989. The average number of papers per firm is just under 60, but most of the 199 firms publish less than half that level. Fifteen firms publish 68% of all scientific papers, with eight of them accounting for 44% of papers.

Four industries account for 73% of papers: electronics, computers, chemicals, and pharmaceuticals. These industries are generally called high-technology industries and they are well known for investing most in R&D. These four industries produce 64% of patents, with electronics and chemicals alone accounting for 52%. However, while industries traditionally identified as science-based (chemicals/pharmaceuticals, electronics/computers) are, not surprisingly, the industries which publish the most scientific papers, they are far from being the only industries to publish. A second group of industries, composed of instruments, mining, aircraft, motor, and metal, publish 16% of papers and produce 25% of patents.

Industrial publications of the 199 multinationals are concentrated in physical sciences and in engineering and technology which account for 54% of the total. Life sciences accounts for 29% of papers, and chemistry 15%. There seems to be a complementarity between two main groups of sciences: physical science and chemistry. The former is produced in industry, while in the latter case it is expertise from outside which is used by industry. We have suggested that this phenomenon reflects the different degree of appliedness of the two fields in industry.

As expected, a large share of papers has been found to involve applied research. However, more interestingly, a greater share has been identified as science rather than technology. 70% of papers are concerned with science, and 29% with basic science, a percentage only slightly higher than the one of previous studies. On a four-level scale, industrial research is nearer the science end than the technological one (2.8).

Physical science is highly correlated with three broad classes of patents (information–telecommunication, equipment–apparatus–instruments, and transport). Life science is mostly connected to drug patents. Chemistry is related to both of these classes of patents. Patents not usually identified as 'science-based' have appeared from our analysis. These are the patents for processes, equipment, and instruments. They are linked to science in industry as much as other patents originating from high-technology industries.

Overall, high-technology industries appear to be more concentrated in terms of papers and patents than the other industries surveyed here. The latter are more diversified: some, like metals, are highly concentrated, while others are more dispersed. This is the case of mining and aircraft. Some lie in between these extremes, for example the instruments, mechanical, and automobiles sectors. Among these more diversified industries, mining, instruments, and automobiles make a significant use of chemistry as well as physics and engineering.

In the end, what can we say about science in industry. Is industry becoming science-based, as bibliometric studies of citations in patents say (Narin and Noma, 1985)? Our answer is twofold. Firstly, industry, as measured by 199 multinationals, increased its publications by 20% between 1980 and 1989, a large increase when compared to the growth of patents, for example. Moreover, this production is no longer due to science-based firms only: some other industries are increasingly publishing. However, and secondly, the growth of publications only followed the growth of articles in SCI as a whole, which is also 20% over the same period. Moreover, the share of the 199 multinationals in the SCI articles remained constant between 1980 and 1989 at about 3%.

This now leads to an important question: how should a science-based industry be defined? In other words, to what extent is a science-based industry one which uses science or one which performs science? If we choose the last definition, do we mean the industry produces scientific knowledge or technological knowledge, basic knowledge or applied knowledge? And if it uses science, do we mean that the industry uses this science directly as knowledge or as embodied in artifacts incorporated in processes? These are basic questions of definition which have still not been adequately addressed by anyone, but for which our study highlights the particular importance.

Our data call into question accepted definitions. When we speak of science in industry, it appears that we should systematically:

1. Distinguish between industries: although the volume of scientific publications is larger in high-technology industries, other industries produce science and they do so with a patents/papers ratio that is comparable to the former; they also publish in several fields.

2. Define the level of science: even in industries traditionally identified as science-based, the larger component of science is generally applied.

3. Compare scientific knowledge with technological knowledge (instead of basic research with applied research, and indeed instead of confusing both of these): seen in this way, industry produces more science knowledge than technology, at least in papers.

What should be investigated in the future is the flow of knowledge between academics and industrialists. Despite all the rhetoric about the usefulness (or non-usefulness) of academic research for industry, there have been surprisingly few studies attempting to establish who industrial scientists cite. We only know that industrial papers, when they exist, cite relatively little science. However, they cite some science. Could it be that, not having to gain recognition by way of citation, they cite only the most directly relevant science? On the other hand, various studies have shown that patents cite science increasingly. How can we explain this difference in the citing practices of the same actors: not citing science in papers, but citing science in patents?

What we have contributed to this research program is that 'science' needs to be better defined in science and technology studies, particularly in terms of disciplines useful to specific industries, but also in terms of levels of research and in terms of the balance between the 'doing' and the 'using' of science.

Appendix A

Table A.1
List of firms in the database

Aerospatiale	Carl Zeiss	GE
Aisin Seiki	Caterpillar	Gebruder–Sulzer
AKZO	Celanese	General Mills
Allegheny	CGE	General Dynanic
Allied	Champion	General Foods
Allis Chalmer	Chevron	Gilette
American Home Product	Ciba Geigy	GM
American Standard	Clark Equipment	Goodyear
American Hospital	Colgate–Palmolive	Grunman
American Cyanamid	Combustion Engineering	GTE
AMF	Continental Gummi	Gulf Western
AMP	Corning Glass	Gutehoff
ASEA	CPC	Halliburton
Ashland	Daimler Benz	Hanson
Atlantic Richfield	Dart	Henkel
AT&T	Dayco	Hitachi
British Aerospace	Deere	Hoescht
BASF	Dow Chemical	Honda
Bayer	Dresser	Honeywell
Beatrice	Dunlop	Hughes
Beecham	Dupont	IBM
BF Goodrich	Eastman Kodak	Imperial Chemical
Boehringer–Mannheim	Eaton	Inco
Boeing	Eli Lilly	Ingersoll
Borg Warner	Emhart	International Harvester
British Petroleum	Esmark	ITT
Bridgestone	Ethyl	Johnson & Johnson
Bristol-Myers Quibb	Exxon	JP Stevens
Brown Boveri	Fiat	Kidde
Brunswick	FMC	Kimberley–Clark
Burlington	Ford	Konishiroku
Burroughs	Fuji	L'Oréal
Canon	Fujitsu	Lear–Sigler
Lockheed	Péchiney	SKF
Lucas	Pfizer	SmithKline
Mannesmann	Philip Morris	SNECMA
Mamom	Philip Petroleum	Sony
Martin Marietta	Pilkingson	Sperry
Matsushita-Electric	Pillsbury	Standard Oil
Mazda	Pioneer	Stauffer
McDermott	Pitney-Bowes	Sumitomo Chemicals
McDonell Douglas	Plessey	Sun Oil
Mead	Polaroid	Tenneco
Merck	PPG Industries	Texaco
Michelin	Proctor & Gamble	Texas Instrument
Minolta	Quaker Oats	Textron
Minesota-Mining	Ralston Purina	Thompson Brandt
Mitsubishi Electric	Raytheon	Thyssen
Mobil	RCA	Toshiba
Monsanto	Rhone Poulenc	Toyota
Motorola	Ricoh	TRW
Nabisco Brands	RJ Reynolds	Unilever
NCR	Robert Bosch	Union Carbide
Nestlé	Rockwell	Union Oil

Table A.1 (continued)

Nippodenso	Rohm Haas	Uniroyal
Nippon Electric	Rolls Royce	United Technologies
Nippon Steel	Saint-Gobain	Upjohn
Nippon Gakki	Sandoz	US Steel
NIssan	Sandvik	Voest Alpine
Northrop	Shering Plough	Volkswagen
Northwest Industries	Schlumberger	Westinghouse
Occidental Petroleum	SCM	WR Grace
Olin	Shell	Xerox
Outboard	Siemens	Yamaha
Owens Corning	Signal	Yoshida
Owens-Illinois	Singer	Zenith

Appendix B

Table B.1
Breakdown of R&D by industries (1983–1989)

Industry	R&D ($ millions)		% change 1983/1989
	1983	1989	
Aerospace	2575	3936	52.8
Automobiles	5090	10284	102.0
Chemicals	3354	4752	41.6
Pharmaceuticals	3422	5143	50.2
Electrical	1690	689	−59.2
Electronics	1592	2216	39.1
Food	656	459	−30.0
Fuels	2366	2479	4.7
Computers	7171	15248	112.6
Instruments	894	1431	60.0
Machinery	1098	2796	154.6
Metals	384	293	−23.6
Semiconductors	734	2155	193.5
Telecom.	1295	3304	155.1
Textiles	75	49	−34.6
Forest	300	432	44.0

Source: *Business Week*, 1984, 1990.

Appendix C

Table C.1
Patents broken down by industrial sector (%) (1986–1989)

Patent	(sector)	CH	PH	MI	TE	PL	FOR	FOO	BE	NO	MET	MEC	EL	CO	IN	MO	AI	TR	MU	TOTAL
Inort. chemicals	(P1)	370									36		71				39		33	941
Org. chemicals	(P2)	7680	1125	556									877		374					10612
Agric. chemicals	(P3)	908	22	111							24								14	1079
Chemicals processes	(P4)	2012	35	1163						29			590	298					152	4279
Apparatus chemicals	(P5)	554		1183						53		100	182		58	50	194			2374
Oils	(P6)	190		2121						171							200			2682
Bleaching, etc.	(P7)	522	62		9			11			7								4	615
Drugs	(P8)	1961	2433																	4394
Food and tobacco	(P9)	135	7					447	119											708
Plastics	(P10)	339		28		372				18			59							816
Non met. minerals	(P11)	787								834			414				97		251	2383
Metal processes	(P12)	90									147		653	45		95	138		106	1274
Metal equipment	(P13)					66					215	329	217			84	84		79	1074
Misc. metal products	(P14)	266		105			173			200		146	93		589	350	183		75	2180
Gen. ind. eq. (non-elec.)	(P15)											303	1285	93		1444	427	180	743	4475
Gen. ind. eq. (elec.)	(P16)	109						76					1441	79		299	192		59	2255
Specialized ind. eq.	(P17)	192		21								702	272	271	37	84	69			1648
Assembling app.	(P18)	142										116	179	175	152	33	27		61	885
Nuclear	(P19)		9									84	361		6	12	80			552
Power plants	(P20)											48	252			274	147		95	816
Road vehicles	(P21)										48	200	186			2744			110	3288
Transport (others)	(P22)											302	16			372	206	21	35	952
Aircraft	(P23)												17	2		33	166		9	227
Mining	(P24)	84	955								39	106			298		151			1633
Telecommunications	(P25)												2991	515			170		318	3994
Semiconductors	(P26)												2061	713			139		54	2967
Electrical devices	(P27)												5191	312		137	132		975	6747
Computers	(P28)												3448	1932	335					5715
Image and sound	(P29)	15											2138	51	342	69				2615
Photo	(P30)	817											335	730	1386				158	3426
Instruments	(P31)	1331	285										2705	513	1366	154	167		288	6809
Textiles	(P32)	24	10		22		9	9			6	7			5	132	17		2	243
Total (100%)		18528	3979	6644	31	438	182	543	119	1305	522	2443	26034	5729	4948	6366	3025	201	3621	84658

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