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In search of the European Paradox: an international comparison of Europe's scientific performance and knowledge flows in information and communication technologies research

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Abstract

This article deals with the scientific performance of the European Union (EU) in what is now perhaps the most important enabling technology worldwide: information and communication technologies (ICT). The performance measures are based on the stock and flows of scientific knowledge embodied in research papers published in international scientific and technical journals. Quantitative data derived from these papers are used to examine and compare the performance of the EU science base with the US and Japan—two leading scientific nations in ICT research, and major competitors in ICT industries. These bibliometric indicators characterize and compare these three ICT research bases in terms of research output, international scientific quality, transnational knowledge flows, and domestic and international cooperation patterns. The analysis focuses on the key issue whether or not these data bear evidence of the perceived 'European Paradox' which is, among others, characterized by a strong EU public sector science base coupled to a relatively weak R&D performance of EU firms. The findings provide empirical confirmation for the existence of this Paradox in both ICT research domains under investigation: computers and data processing, and telecommunications.

Keywords: Information and communication technologies; Bibliometric indicators; Research output; Scientific cooperation; Citation analysis

1. Introduction

1.1. The European Paradox and the information and communication technology (ICT) sector

Knowledge has always been central to economic development, competitiveness and wealth creation. But only over the last few years has its relative importance been recognized, just as that importance is growing in advanced industrialized nations. The determinants of success of national economies is ever more reliant upon their effectiveness in gathering and utilizing knowledge. The term 'knowledge-based economy' results from this fuller recognition of the role of knowledge in economic welfare and growth (OECD, 1996). These knowledge-based economies are characterized by industrial and service innovations that are increasingly driven by the interaction between producers and users in the exchange of both codified and tacit knowledge. Knowledge-based business enterprises are now more strongly dependent on strategic know-how and competences that are being developed interactively and shared

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within networks, where know-who is just as significant as know-how and know-what. The newly acquired relevance of knowledge is intricately linked to advances in ICTs and the ubiquity of successful applications, such as personal computers, World Wide Web, electronic databases and mobile phones. These devices, facilities and services can be regarded as both cause and effect of the need for collecting and handling of large quantities of data and information more effectively (OECD, 1997).

ICT manufacturing and services industries, and their underlying R&D and technological innovations, are clearly of vital economic importance to the European Union (EU) and its knowledge-based economies. However, European competitiveness in the ICT sector seems to be deteriorating in recent years. Analysts tend to benchmark the economic performance of the EU by comparing its strengths and weaknesses to the accomplishments of the US and Japan, the two other regions of the 'Triad' trading block (e.g., EC, 1997). The findings are not very encouraging. EU market-shares in ICTs are dropping (Booz et al., 1997). The EU accounts for a relative small, and declining, share of patents granted in the both the European and US patent system in various ICT-related areas (computer and office machinery, electronics, and instruments) indicate significant weaknesses in the EU's technological performance (EC, 1997). Moreover, EU R&D intensity (i.e., R&D expenditure as percentage of production) are relatively low in computers as compared to the situation in the US and Japanese ICT manufacturing industry. However, the EU's R&D intensity is on a par with the US and Japan in the electronics sector (including telecommunications equipment). In contrast, the EU's research base in the natural and engineering sciences appears to be of high quality and comparable with the US and Japanese research performance (EC, 1997). However, to be among the leaders in science is neither a necessary nor sufficient condition to be competitive or pre-eminent in producing ICT products for world markets. Nevertheless, the quality of the public science and engineering infrastructure and its links to EU industry may be one of the most important assets for supporting ICT innovations.

This set of findings indicate that the research bases and innovation systems in EU countries appear to be less effective in developing and exploiting ICTs, and related ICT products, for the marketplace. In other words, the EU is failing to commercialize its R&D activities and inventiveness and unable to reap economic and employment rewards of its own achievements. Numerous studies have provided evidence of the fact that several handicaps lay at the heart of what is sometimes referred to as the 'European Paradox' (e.g., EC, 1996).[1] This article explores one of the perceived deficiencies in upstream activities of the EU ICT innovation system: the knowledge exploitation gap in the science–technology interface, which is among others marked by insufficient cooperation and ineffective knowledge transfer between academia and industry. In addressing this issue, we focus on the following three key features of the EU ICT science base:

1. science-intensity of EU industry;
2. public–private cooperative links;
3. knowledge flows of EU scientific knowledge within and outside the EU.

Each of these aspects will be dealt with in terms of quantitative measurements and bibliometric analyses that are applied to various characteristics of ICT research papers published in international scientific and technical journals. The associated 'science indicators' supply empirical data that enable a detailed comparison of the performance of the EU, USA and Japan in the global ICT science base.

1.2. Corporate ICT innovations and the public science base

Many ICT innovations on the market are produced either by the major computer manufacturers, the multinational consumer electronics companies or by the large telecommunication operators, in order to achieve a lead in the niches they occupy in global

[1] The 'European Paradox' is comprised of an interrelated set of constraints and deficiencies hampering innovation activities, amongst others: (1) insufficient identification of market and societal needs, (2) lack of supportive external business environment, (3) lack of entrepreneurial motivation and aversion of risk among investors, (3) lack of transparency in regulation and intellectual property protection, (4) public attitudes concerning real and potential dangers of technologies, (5) insufficient investment in R&D, (6) institutional and geographic fragmentation of R&D efforts, and (7) insufficient linkage between research output and applications.

markets. These innovations are a major driving force of their competitiveness. Nowadays, these corporations are faced with both internal pressures (tighter budgets and rising costs, deregulation and privatization) and external competitive pressures (technology races, shorter development cycles and global competition). As a consequence, ICT manufacturing and services firms often face fierce competition which forces them (1) to focus on their core competences, (2) to carry out relatively high levels of R&D—either in the home country or in host countries, and (3) to specialize in the primary scientific disciplines underlying their core technologies and strategic niches to ensure the firm's technological leadership. These pressures have not only created considerable technological development activity in corporate R&D units, but also forced them to shift the focus of their research programmes towards application oriented research and short-term objectives.

The development of innovative ICT products, processes and services is usually carried out within the framework of corporate R&D projects that are an integral part of the firm's established ongoing innovation activities. However, the innovation process often entails considerable interaction and feedback between manufacturing, marketing, research, and further technological development (design, testing, prototypes). Although strengthening of the corporate research base and diversification of research portfolios is now often considered less significant than developing new technologies and meeting market needs, ICT corporations at the technological frontier recognize that future technological advances and innovations require exploitation of new opportunities created by basic and applied research. To ensure a steady flow of innovations, R&D-intensive firms need to have the competitive edge of knowing the state of the art in the various fields of information technology and related scientific research. Maintaining a lead requires investments in long-term R&D to enable acquire and upgrade relevant competences (i.e., leading-edge knowledge, techniques and skills).

The complexity of these innovation processes and the need to balance both short-term and long-term R&D objectives has promoted a need among R&D units to achieve economies of scale and scope. In fact, corporate research laboratories of large innovative multinationals increasingly position their activities in the right niches and strategic environments, and extend their activities into novel research areas and establish new contacts. In doing so, many corporate laboratories have become more of a network type of organizational unit within the firm and its R&D environment, and are characterized by many intramural and external R&D partners and intensive customer–contractor interaction (e.g., Miller, 1995; Pearce and Papanastassiou, 1996).

Optimization of corporate ICT research forces companies to tap into several reservoirs of knowledge and skills—either in-house or through collaborative arrangements with others. External inputs to this process may involve contributions from parent firms or subsidiaries, or from a variety of 'upstream' and 'downstream' resources and institutions such as customers and suppliers, other companies through joint ventures, consultancy firms and universities (e.g., Arundel et al., 1995). As a result of the increased pace of scientific and technological advances, many large and diversified ICT firms now need to keep in touch with developments in more scientific fields and areas of science-based technologies than can be covered by their in-house R&D efforts. They have therefore forged links with the public research sector either through consulting services, outsourcing of contract research or joint R&D projects. The chief aim is to access and explore new technological developments and to receive concrete results from fundamental and applied research with immediate or potential relevance for their own in-house R&D programmes (e.g., Mansfield, 1995). These public–private linkages and knowledge transfers have been an integral part of R&D strategies for many years. For example, many scientific instruments developed in fundamental research have been transferred on a large scale to the ICT industry: "Indeed much, perhaps most, of the equipment that one sees today in an up-to-date electronics manufacturing plant had its origin in the university research laboratory" (Rosenberg, 1992).

Those public sector research institutes and universities are key performers of high quality generic research in areas such as semiconductors, integrated circuits, and opto-electronics. In doing so, they provide direct support to commercially oriented and mission-driven research aimed at generating new production technologies, products and services. They ensure a steady supply of new techniques and equipment, up-to-date knowledge on leading-edge scientific developments, as well as understanding of theoretical foundations and innovative ideas. [2] Moreover, basic academic research activities provide a fertile ground for high-level training of skilled technologically-oriented PhD researchers and engineers whose knowledge and experience can be utilized in corporate R&D activities. Hence, the public research sector produces a body of scientific knowledge for industry and serves as an overall repository of scientific and technological knowledge, which helps enterprises reduce research costs, strengthen their R&D capabilities and enlarge the technological portfolio.

2. Methodology and information sources

2.1. Applying bibliometrics to ICT research outputs

ICT research activities may encompass both fundamental and applied science as well as basic ('public') technology. R&D outputs can be quite divers, ranging from tacit knowledge (experience, 'know-how' and 'skills') to hardware and software, designs, materials, prototypes and other 'artefacts', as well as codified written knowledge. As for the latter type of output, the bibliometric approach is based on the assumption that many new ideas and knowledge generated within the public research system normally reach a published form at some stage because publishing has traditionally been at the core of validating and distributing knowledge. These papers generate knowledge and describe know-how and skills which are disseminated and further utilized in developing and testing technical concepts and devices which in turn are brought to bear on industrial innovations. A fair share of these research publications originate from universities and research institutes and emerge in the mainstream scientific literature as research articles in international scientific and technical journals.

[2] Fundamental scientific knowledge offers intellectual assistance to applied researchers—whether in the public or in the corporate sector—on the possibilities to derive time- and cost-saving guidance as to how best to proceed in searching for ways to achieve technical objectives.

Bibliometrics is obviously less useful in the corporate domain of the ICT sciences, where research is meant to help generate new product and process possibilities, and not primarily intended to produce publishable results. Private enterprises strategically manage their basic and applied research by means of secrecy and appropriating results, and do not generally reward their researchers for publishing. Codified knowledge of industrial-relevant ICT research is therefore less likely to circulate freely through generally available scientific publications. However, many R&D-intensive firms do publish research papers—and some of them publish quite a lot. These companies have good reason to publish some of their scientific and technical research—especially in those cases where firms must invest in longer-term fundamental research to create in-house capabilities for recognizing, assimilating and exploiting knowledge created elsewhere, and that need to establish or improve their links with the public research sector (e.g., Hicks, 1995). Commitment to such broad-scope long-term basic research projects requires continuity in funding and a relatively stable institutional environment that can only be achieved by the larger firms with a strong market position and a good prospect of a sustained presence in science-based ICT manufacturing and services sectors. These external demands have forced corporate researchers at these large enterprises to adapt their publication strategies in favor of more publications in the open scientific and technical literature. In doing so these firms release information on their in-house scientific and technical capabilities to the outside scientific community and thus present themselves as an acceptable player in the techno-scientific arena and its technological alliances and R&D networks (e.g., Debackere et al., 1994). Research papers by industrial researchers should therefore be regarded as deliberate signals of the existence of tacit knowledge and skills in order to enhance visibility and to build credibility which is needed for R&D partnering and exchange of scientific and technical knowledge. These publications may also help create and maintain the external image of a company's technological leadership.

Clearly, companies publish only a fraction of their documented scientific outputs. Before a company publishes research results, the paper is screened and publication of commercially sensitive information will be blocked in order to balance the corporate need for secrecy with the advantages of pursuing a strategy of openness.[3] Scientific articles—like patents—secure knowledge claims but need not disclose everything. Much of industry's R&D publications are disseminated through company journals, conference proceedings, or through research articles in the domestic serial literature.[4] Bibliometric indicators based on articles in international journals will tend to emphasize basic research output and underestimate the level of applied industrial research. As a consequence, applied corporate ICT research, especially in areas where strategic interests prevail, tends to be poorly represented in scientific publications in the open literature. Despite these limitations, international journal articles can still provide interesting information on the science intensity of companies, especially for the major science-based multinational companies and large private R&D laboratories who produce large quantities of research publications in the international scientific and technical journals (Godin, 1996; Hicks et al., 1996). For example, Philips, the Dutch electronics company, publishes some 200 of these articles each year—as much as a medium-sized European university (Tijssen et al., 1996).

A fraction of industry's research papers are co-authored with public research institutes and universities. These papers reflect successful scientific cooperation between industry and the public sector, and are likely to signify related knowledge flows and R&D networking activity between corporate researchers and academic scientists. These joint research papers may not only signify the completion of successful research involving public and private sector researchers, but also indicate research topics and areas where industry is more inclined (or forced) to collaborate externally due to lack of specific in-house knowledge or facilities (Tijssen et al., 1996).

On the whole, ICT research papers in international scientific and technical journals provide a source of empirical information on key features of ICT science bases around the world. These papers not only indicate the presence of international mainstream research activities and scientific collaboration but can also indirectly gauge the existence of high quality scientific and technical capabilities. Quantitative data derived from research papers enable first-order approximations of levels of research activity and scientific performance of major research institutions, large science-based private enterprises, and aggregates thereof such as institutional sectors, regions and countries.

2.2. The ICT research database

This bibliometric analysis draws on bibliographic records extracted from a specially developed relational database on worldwide ICT-research output. It incorporates more than 50,000 research papers in international scientific and technical journals that are also covered by the *Institute for Scientific Information* for its *Science Citation Index* (SCI) database. The SCI indexes some 3500 international scientific and technical journals, including all influential peer reviewed journals in the natural and life sciences. Research articles in the SCI-covered international journals disseminate results of high quality research throughout the worldwide scientific community. The large set of SCI-covered journals is generally considered to provide, on the whole, a satisfactory representation of internationally accepted ('mainstream') fundamental research which is carried out in industrialized nations.

The ICT papers were selected from two international databases: *INSPEC* and *Compendex*, both dealing with research in the natural sciences and engineering. INSPEC is the foremost bibliographic database covering research output in electrical engineering, electronics, computing and information technology, and physics. Compendex provides a

[3] Publication delays may be imposed to secure its lead over competitors, or suspension of publication until related patents have been filed. In cases where patentable assets cannot be gained, publications might be used primarily as a vehicle to secure the claim on the intellectual property of the underlying ideas, technical specifications, or methods and techniques.

[4] The national journals often play an important role in the local diffusion of applied knowledge, particularly to the industrial sector. These journals are better suited to reach local audiences and matters of local interest. Most conference proceedings are presumably used in preference to scientific journals because of the shorter time-lag involved. Papers in these (non-refereed) proceedings are usually not as extensive or definitive as those published in refereed non-letter journals.

broad coverage of the engineering sciences. The analysis concerns all SCI-covered research papers with at least one INSPEC and/or Compendex subject classification code explicitly referring to either *Computers–Hardware*, *Computers–Software* or *Telecommunications*. This study will deal only with the data at the macro level, that is, its two major research domains: *Computers and Data Processing* (comprising of 80% of the papers), and *Telecommunications* (20%). The core of these papers are concentrated in the following scientific disciplines: electrical engineering, computer sciences, applied physics, applied mathematics, information science, telecommunications, optics and acoustics (Tijssen and van Wijk, 1998b). Further background information about this database and its general contents is provided by Tijssen and van Wijk (1998a).

2.3. Mapping knowledge flows and measuring scientific impact

The records in the CWTS ICT database include the full list of authors and their affiliate addresses, as well as the reference list with citations to the earlier research literature. Both bibliographic items can be used to help characterize the ICT science base in the EU and discern features that can be utilized for tracking down and describing features of a European Paradox with ICT research. Pairwise analyses of those affiliate addresses has become a conventional way of tracing cognitive and institutional links between public sector researchers, and also offers the possibility of performing aggregate-level quantitative studies of cooperation patterns and networking (e.g., Luukkonen et al., 1993). As for the collaborative links between the public sector and corporate sector, joint projects involving applied research are less likely to give rise to these co-authored research papers in view of their restrictive knowledge dissemination strategies and appropriation regimes. However, joint public–private undertakings with shared resources that are primarily aimed at developing new basic knowledge and know-how are more prone to generating joint papers, especially when these collaborative projects include contributions from academics which are particularly focused on producing international research papers to enhance visibility and prestige.

Co-authored scientific papers not only indicate scientific cooperation and research partnerships, but —indirectly—also signify transmission of knowledge and skills. Other features of knowledge transfer processes are made visible through the reference lists of research papers in which authors explicitly cite their sources. These citation flows and cooperation links enable systemic measurements of disembodied knowledge flows within the ICT science base. This empirical information will be used to determine the geographical distribution of partnership ties among countries and citation flows which provide insight in the direction and intensities of transnational knowledge 'spillovers'.

Citation analysis is also a useful bibliometric tool for gauging the relative scientific standing of the research papers and the institutes and countries from which those papers originate. The number of citations received by a scientific paper is considered a proxy indicator of its impact or influence on the scientific community. [5] More specifically, the number of citations received by research papers that were published in SCI-journals and issued by other SCI-covered papers helps gauge the international scientific visibility and impact of research outputs. High citation scores tend to reflect the underlying scientific quality of work and the scientific leadership of research-performing groups and institutions involved. Using these citation impact scores as an indicator of scientific quality offers the benefits of comprehensiveness and objectivity at high aggregate levels where experienced assessment of subject experts will not stretch further than a qualitative view of a limited domain and can no longer produce equally valid conclusions. [6] It is also important to note that this application of citation analysis to the

[5] Citation distributions are very skewed. For example, more than 70% of all publications in the SCI-covered journals assigned to the engineering sciences were never cited in 5 years (Pendlebury, 1991). Moreover, usually only a small share of the papers may account for well over a half of the citations.

[6] Note that visibility and quality of research cannot be fully assessed by applying citation analysis. A balanced judgement requires supplementary qualitative assessments (generated through peer review panels, surveys, interviews, etc.) in conjunction with other quantitative measures of esteem—methods which, on their part, also have their own problems and biases.

Table 1
Scientific publication output of Triad regions in international research papers, 1993–1996[a,b]

	Percentage of global output	Percentage output by private sector
Computers and data processing		
USA	43.6	22.0
EU-15	25.4	11.1
Japan	6.5	46.6
Telecommunications		
USA	38.1	41.8
EU-15	20.3	34.1
Japan	12.4	78.8

[a] Based on country(ies) listed in affiliate address.
[b] Papers attributed according to a whole counting scheme (multiple counts of papers involving more than one country).

ICT research base is likely to produce an underestimation of true scientific impact. Particularly in ICT-areas where researchers and engineers concentrate their activities on technologies (e.g., construction and testing of computer hardware or scientific instruments), and are consequently in most cases not properly credited in terms of citations from related scientific and technological literature (see e.g., Le Pair, 1988). Similar R&D activities by academics at technical universities may also run the risk of going largely unnoticed in terms of citations (Winkel-Schwarz et al., 1998). Citation analysis will however provide useful quantitative information regarding the use and dissemination of knowledge produced in areas of basic science and engineering relevant to ICT.

3. Is there a European Paradox?—Results of the bibliometric analyses

3.1. Is the ICT industry in the EU sufficiently active in basic research?

Table 1 shows a corporate sector that accounts for a substantial share of the worldwide research output and is producing large numbers of research papers in international scientific and technical journals. These data strongly suggest that science-based firms and private R&D laboratories appear to are more than mere 'free riders' on world science and are in fact be contributing significantly to our publicly available, new knowledge. The data presented Table 1 also clearly suggest that EU industry is lagging behind in terms of its participation in scientific papers. Only 11% of the EU papers in the area of computers and data processing belong to the private sector, whereas US firms account for 22% of the US publication output while their Japanese counterparts contribute nearly half of all Japanese research papers. The situation is somewhat better in telecommunications research where EU firms (co-)author 34% of the papers, but this fraction is still significantly below the figures for the US (42%) and Japan (79%).

Judging by the significant gap in propensity for scientific publishing, US and Japanese ICT companies seem more research-intensive than EU firms. Note that the extremely large share of Japanese firms is a general characteristic of the entire Japanese science system (although a considerable fraction of those papers are directly attributable to specific large science-based enterprises such as Hitachi and NEC). The substantial contribution of the US private sector is largely explained by the output of IBM's *Yorktown Heights Laboratories* and the AT&T *Bell Laboratories,* [7] both comprising of large research facili-

[7] AT&T was split in 1996 into three new companies: AT&T (communications services), Lucent Technologies (systems and technology) and NCR (computers). Parts of AT&T Bell Laboratories went to AT&T (AT&T Research) and Lucent Technologies (Bell Laboratories Research).

ties and resources devoted to conducting research aimed at exploring the frontiers of science.

The overall share of Japan in the global ICT research output is quite modest considering that Japanese firms account for about a third of the EPO and USPTO patents in electric and electrical components/telecommunications equipment, and well over 10% of the patents in the computers sector (EC, 1997; OST, 1998).[8] One of the more plausible reasons for this significant discrepancy is the reluctance of Japanese researchers to publish their research results in international (English language) peer-reviewed scientific and technical journals. Furthermore, a very large share of the Japanese papers are produced by industrial researchers who are likely to be more restrained by knowledge dissemination and publication strategies of their companies, as compared to their colleagues in the public sector.

3.2. Is the EU ICT research really of international top quality?

As explained in Section 2.3, citation counts provide proxy measures of scientific impact and quality. These impact indicators were used to ascertain whether or not European science is indeed, as implied within the concept of the European Paradox, of the highest international quality.[9] The citation scores in Table 2 show that this is indeed the case.

Table 2
Citation impact of most highly cited countries: average number of citations received by 1993–1994 research papers[a]

Computers and data processing[b]		Telecommunications[c]	
Country/ Triad zone	Impact	Country/ Triad zone	Impact
Switzerland	2.77	Sweden	3.32
Germany	1.90	Germany	2.84
Austria	1.66	Great Britain	2.81
Sweden	1.66	**Japan**	**2.80**
USA	**1.63**	Switzerland	2.69
Great Britain	1.61	**USA**	**2.65**
Netherlands	1.56	**EU-15**	**2.53**
Portugal	1.53	Spain	2.39
Italy	1.52	Italy	2.26
Spain	1.45	Denmark	2.22
Russia	1.36	France	2.11
EU-15	**1.35**	Netherlands	2.08
France	1.31	Ireland	1.93
Belgium	1.30	Australia	1.87
Ireland	1.25	Finland	1.73
Canada	1.24	Russia	1.71
Australia	1.23	Portugal	1.65
Japan	**1.23**	Canada	1.46
Israel	1.20	Belgium	1.10
Finland	1.14	Israel	1.04
Singapore	0.80	Taiwan	0.90
India	0.80	Singapore	0.83
Greece	0.76	China	0.82
China	0.71	Austria	0.79
Taiwan	0.65	South Korea	0.74
South Korea	0.60	Greece	0.44

[a]Citation time periods: 1993–1996 for 1993 papers, 1994–1996 for 1994 papers.
[b]EU member states (except Luxembourg) and other countries with at least 200 papers over the period 1993–1994.
[c]EU member states (except Luxembourg) and other countries with at least 50 papers in 1993–1994.

Europe is good at basic ICT research, where Switzerland, Sweden, Germany, Austria and Great Britain top the lists. The scores of the EU as a whole compares reasonably well to those of the US and Japan, ranking second in computers and processing (way behind the US), and third in telecommunications research at close distance behind Japan and the US. It is also worth noting that some non-Triad countries such as the Russian Federation,[10] Australia and Canada rank in the upper or middle sections of this world league. Research from other countries like Israel and some of the newly industrialized Asian nations (notably, Singapore, Taiwan and South Korea) are less visible in terms of citations in the

[8] Japan accounts for 36% of the OESO business R&D expenditure in 1993 the area of computers, while the North America (US, Canada, Mexico) accounts for 42%, and the EU-4 (UK, France, Germany and Italy) for 19% (OECD, 1997). The corresponding data for telecommunications are 24%, 38%, and 31%. Further data on worldwide ICT markets shows a 14% share for Japan, 34% for the US and 32% for Western and Eastern Europa (EITO, 1996).

[9] Note that citation frequency data tend to be discipline-dependent. Different ICT research fields and subfields may have slightly different citation propensities and thus generate different levels of citation impact. We will assume that this effect is neglible at the aggregate of level of (supra)national ICT science bases in the advanced countries where all major ICT research fields will be covered to a sufficient degree.

[10] The data pertain to research done in the years 1990–1992, the early stages in the demise of the Russian research system.

mainstream international scientific and technical literature.

Telecommunications research attracts much more international citations per paper on average, which can be taken as an indication of cognitive differences between both ICT research domains in terms of their international orientation and internal dynamics (i.e., speed of scientific publication and citation communication practices). Moreover, the distribution of impact scores across countries shows a much wider range as compared to computers and data processing. Highly cited telecom research papers tend to originate from the advanced industrialized Western countries, which have the competitive advantages of high quality science bases to match the needs of their more sophisticated ICT infrastructures and industries.

The publication output of most EU countries are determined by relatively few large public sector institutions, and some major R&D-based enterprises. Focusing on the most prolific large institutions in terms of scientific publication activity in international scientific and technical journals, provides a way of identifying the main players within the EU, and comparing their scientific impact with each other and—more importantly—with other major institutions in the US and Japan. [11] Table 3a presents the data on computers and data processing, which on the whole reflects the ranking of the EU, US and Japan as shown in the previous table. Somewhat surprisingly, the University of Cambridge ranks number one—and not of one of the renowned US institutes such as MIT or Stanford which one might expect considering the relatively high impact of the US as a whole (see Table 2).

More interesting is the difference between the performances of the EU public sector and its private sector. The research papers originating from EU enterprises appear to be less frequently cited by the international scientific community—both in comparison to EU research universities as well as other large US and Japanese ICT companies. Research papers of the British Telecom laboratories are the exception receiving more than three citations per paper on average and boasting citation scores that are twice as high as those of Thomson, Philips, Siemens and Alcatel–Alsthom. These findings suggest that basic research at these EU multinational enterprises (MNEs) is of less significance to the international frontiers of fundamental research as compared to research efforts of their counterparts in the US and Japan. This outcome may indicate a poorer quality basic research by EU industry, but on the other hand may also partially reflect more restrictive publication strategies within EU multinationals, or a stronger emphasis on applied research that is likely to be under-represented in this study.

The relative standing of large EU research institutions and firms is much better in the case of telecommunications research (Table 3b). This outcome is in line with the national rankings shown in Table 2. In fact, EU institutions top the list in both the public and private sector: University of Essex, the French research institute Centre National des Etudes de Télécommunications, [12] and Ericsson, the Swedish MNE. The citation impact of the other large EU companies and telecommunications operators exceeds their performance levels in the field of computers and data processing. The Japanese companies are clearly outperforming the Japanese universities in terms of citation impact: the scores of the national telecommunications operator NTT, Fujitsu, and the overseas operator KDD, are all significantly above the score of the University of Tokyo.

Several institutes and firms feature prominently in Table 3a as well as Table 3b, and are therefore clearly very active in research on computers and data processing, as well as telecommunications research. This finding not only illustrates the close cognitive links between research both ICT domains, but also

[11] Note that these results are vunerable to differences in the research profiles and related technologial portfolios of institutions, where those who are more actively publishing about research on 'hot topics' or active in highly cited research areas are likely to receive more citations on average. A more sophisticated 'like with like' comparsion should be able to reduce these biases, but requires extensive background knowledge about the various actors which was beyond the scope of this study.

[12] CNET is part of the state-owned company France Telecom, but has operated almost as a public research organisation, serving the entire French telecommunications industry. Papers are attributed to CNET and/or France Telecom according to affiliate address listed by the authors.

Table 3
Most highly cited institutions: average number of citations received by 1993–1994 research papers[a]

Public sector institutions[b,e]		Impact	Firms[c,f]		Impact
Computers and data processing					
Univ. Cambridge	EU	3.2	Hughes	US	4.7
Univ. California, Berkeley	US	2.8	British Telecom	EU	3.1
Stanford Univ.	US	2.8	Hewlett-Packard	US	2.8
MIT	US	2.6	Xerox	US	2.6
Univ. Minnesota	US	2.5	AT&T/Bell Laboratories	US	2.4
Kyoto Univ.	JP	2.4	Fujitsu	JP	2.3
Univ. California, Los Angeles	US	2.4	Motorola	US	2.2
Univ. London	EU	2.3	Nippon Telephone and Telegraph	JP	2.2
Univ. Oxford	EU	2.2	NEC	JP	2.0
Univ. Wales	EU	2.2	Bell Communications[d]	US	2.0
Univ. Illinois	US	2.1	General Electric	US	2.0
Univ. Texas	US	2.1	Hitachi	JP	1.9
Univ. Washington	US	2.0	IBM	US	1.8
Osaka Univ.	JP	2.0	Thomson	EU	1.8
Tech. Univ. Delft	EU	1.9	Texas Instruments	US	1.7
Univ. Michigan	US	1.9	Philips	EU	1.7
Polytech. Milan	EU	1.9	Siemens	EU	1.7
Univ. Tokyo	JP	1.9	Intel	US	1.6
Univ. Edinburgh	EU	1.9	Toshiba	JP	1.2
Univ. Leuven	EU	1.8	Matsushita	JP	0.9
Univ. Rome 1	EU	1.8	Alcatel–Alstholm	EU	0.8
Univ. Maryland	US	1.8			
Victoria Univ. Manchester	EU	1.8			
Tokyo Inst. Tech.	JP	1.8			
Tohuku Univ.	JP	1.4			
Telecommunications					
Univ. Essex	EU	5.7	Ericsson	EU	4.6
CNET	EU	4.8	Hewlett-Packard	US	4.5
Heinrich Hertz Inst.	EU	4.6	Nippon Telephone and Telegraph	JP	4.0
Stanford Univ.	US	3.8	British Telecom	EU	4.0
Georgia Inst. Technol.	US	3.1	AT&T/Bell Laboratories	US	3.7
MIT	US	2.6	Philips	EU	3.5
Tech. Univ. Denmark	EU	2.6	Fujitsu	JP	3.2
Univ. California, Berkeley	US	2.4	Siemens	EU	3.0
Univ. California, Los Angeles	US	2.4	Bell Communications[d]	US	2.9
Univ. Strathclyde	EU	2.4	Kokusai Denshin Denwa	JP	2.7
Univ. Illinois	US	2.3	KPN	EU	2.5
Univ. Tokyo	JP	2.3	Alcatel–Alstholm	EU	2.4
Univ. London	EU	2.3	France Telecom	EU	2.0
Univ. California, San Diego	US	2.3	NEC	JP	2.0
Polytech. Milan	EU	2.1	IBM	US	1.7
California Inst. Technol.	US	2.0	GTE	US	1.6
Univ. Southampton	EU	1.9	Hitachi	JP	1.5
Delft Tech. Univ.	EU	1.9			
Royal Inst. Technol.	EU	1.8			
Univ. Maryland	US	1.6			
Univ. Texas	US	1.3			
Osaka Univ.	JP	0.8			

the diversification of corporate R&D portfolios across many ICT areas. Recent research by Gambardella and Torrisi (1998) suggests that this strategy of diversification seems to pay off for electronics companies where technological diversification is positively correlated with their business performance.

3.3. Scientific cooperation in the EU science base: its strength or its Archilles heel?

3.3.1. The public research sector

Ineffective linkages between the science base and innovation systems are considered to be one of the key features of the European Paradox. The transfer of scientific knowledge and skills from the public research sector to science-based companies constitutes one of the dimensions of this interface. Part of the flow of knowledge and know-how is channeled through formal and informal collaborative R&D projects. Scientific cooperation can be considered a major contributor of knowledge transfer across institutional and geographic borders: it not only entails communication, interaction and knowledge exchange from one partner to the other, but also helps increase the general awareness—and often, usefulness—of relevant external knowledge. This section focuses on joint research papers as proxy indicators of successful links between research institutions involved in such collaboration. The authors and institutions listed in the address heading of these co-authored papers provide an entry point for empirical analysis of scientific cooperation and networking in ICT-relevant fundamental research, not only in terms of the worldwide geographic distribution of the co-authors but also the institutional type of partners involved. Analysis of the research collaboration structure in terms of these co-publication linkages sheds light on the occurrence and propensity for public/private partnerships within the EU science base broken down by geographic zones. Comparison with the similar data on US and Japanese research papers provides clues to whether or not the European Paradox reveals itself is terms of relatively low levels of cross-sectoral cooperation and related knowledge transfer.

Table 4 presents data about the scientific collaboration of public research institutions. The scientific partner profiles distinguish between partnerships within the main organization itself (i.e., different departments, laboratories or research units), and external partners categorized by their location in one of the five geographic zones: home country, the three Triad zones, and the Rest of the World (RoW). The data on the external partners is broken down by main institutional sector (i.e., either public or private sector). The findings show that each triad zone is characterized by a strong preference for collaborating with domestic partners, thus reflecting the well-known propensities in communication flows and knowledge transfer—especially those imposed by person-embodied exchanges—due to cultural, geographic and linguistic constraints. Take for example the EU research papers attributed to computers and data processing. Here one finds a 19% share of intramural co-authorship links referring to two or more units/departments within the same main organization. A further 43% relates to domestic partners outside the main organization where 29% list another public sector institution and 14% a firm. US organizations and US firms contribute to 9% of the EU research papers. Japan is of marginal importance with a share of 2%. Co-authorship links with non-

Notes to Table 3:

[a] Citation time periods: 1993–1996 for 1993 papers, 1994–1996 for 1994 papers.

[b] Top 10 most actively publishing main research institutions in the EU and US public sector, and the top 5 Japanese main institutions (output threshold: 70 papers over the period 1993–1996).

[c] Most actively publishing EU and US firms (top 10) and top 5 Japanese firms (with more than 70 papers in 1993–1996). Comprises of private enterprises, private research laboratories, institutions funded (mainly) by the business sector, and (semi)public market-oriented profit-making institutions (e.g., telephone and telecommunication operators, public utilities). Includes the foreign R&D labs of enterprises.

[d] Bell Communications Research (also known as Bellcore) is the joint research center of the regional Bell companies.

[e] Most actively publishing EU and US public sector research institutions (top 10), and the Japanese institutions (output threshold: at least 30 papers in 1993–1996).

[f] Firms with 25 or more papers in 1993–1996.

Table 4
Geographic and institutional distribution of collaborative research papers of public research institutions, 1993–1996 (percentage of co-authorship links)[a]

	Internal partners	External cooperation partners										Total
		Domestic[b]		EU-15[b]		USA		Japan		RoW[b]		
		Public	Private	Public	Private	Public	Private	Public	Private	Public	Private	
Computers and data processing												
EU	19	29	14	16	5	4	5	1	1	11	1	100
USA	36	18	35	3	1			0	1	4	2	100
Japan	16	26	43	4	0	1	3			5	1	100
Telecommunications												
EU	9	13	35	11	15	4	7	1	1	5	4	100
USA	33	16	42	1	2			0	1	2	3	100
Japan	14	17	58	4	1	0	3			4	0	100

[a] Based on the worldwide selection of the 96 most actively publishing universities and public research institutes (see Tijssen and van Wijk, 1998a).
[b] Domestic: home country (for EU nations: intra-country cooperation). EU-15: the 15 EU member states (for EU nations: the other 14 EU member states). RoW (Rest of World): countries outside the EU-15, USA and Japan.

Triad countries account for the remaining 12%, where links with other public research institutions are by far the major contributor (11%). The collaborative ties with Swiss research institutions represent one of the major components in this 12% share.

These co-authorship distributions clearly indicate a relatively small share of EU co-authorship linkages between public and private sector institutions as compared to the US and Japan. In contrast, telecommunications research papers show a level which is much more in line with the US and Japanese situation although Europe is still in third place. It seems that domestic public research bases in the EU countries are indeed less inclined to, or capable of, forging public–private research links at the same level as in the US and Japan.

The data provide empirical confirmation that the various domestic ICT research bases in Europe are becoming increasingly intertwined and interdependent; intra-EU cooperation linkages constitute the second largest category of partnerships within the EU countries. This finding can be ascribed to the general trend toward internationalization of R&D, and the effects of funding by EC Framework Programmes, such as ESPRIT, which are specifically designed to foster R&D cooperation within and between public and private sector and build a European science and technology infrastructure. Moreover, from the viewpoint of the 'integrated EU science base', defined as the sum of domestic and intra-EU links, the EU no longer lags behind the US and Japan in telecommunications research in terms of its propensity for cross-sectoral collaborative linkages. In contrast, the performance of the integrated EU science base improves only marginally in the area of computers and data processing. These co-authorship data also indicate that the EU research system seems to lack the US capability for cooperation between different units of large public research institutions: the share of intra-organizational co-authorship links is two-fold or three-fold higher in the US. Presumably, this finding can be—at least in part—explained by the larger size of many US institutions which provide the economies of scope and scale necessary to assemble enough 'critical mass' in terms of physical and human capital for these close in-house collaborative links. Considering the strength of the US science base, it does not come as a surprise that EU researchers frequently team up with US partners from both the public and private sector, although the relative shares are still quite low compared to the level of domestic and intra-EU cooperation.

In the main, collaborative ICT research within the EU public sector appears to be characterized by four key features: (i) strong collaborative ties and networking within the national research systems—comprising of collaborative links both within and between main organizations; (ii) domestic firms are important partners; (iii) EU institutions are more involved in international collaboration, especially with other EU institutions; and (iv) a relatively strong attraction to the USA as a non-EU foreign partner.

Despite the worldwide significance of ICTs and the increasing internationalization of the underlying R&D, these data also seem to indicate that coopeoation is still largely determined by pre-existing institutional, organizational and cultural barriers that foster and sustain domestic research links. These local constraints are a key determinant in scientific, technological and institutional change. Given the fact that national research and technological capabilities can be regarded as a cumulative process building on prior R&D infrastructures, knowledge and know-how, one may expect many countries, like the US and Japan, will continue creating and distributing their ICT knowledge results within their domestic science base. The situation is noticeably different in the case of the EU. Here, we find a relatively small propensity for domestic partnering which is compensated by a relatively strong tendency towards intra-EU research partnerships. There is clearly a European dimension to collaborative ICT research in the different EU member states—particularly within the public research sector, which now seems to have reached the same level as domestic cooperation (in telecommunications) or at least half that level (in computers and data processing).

3.3.2. The corporate research sector

Large MNEs [13] are the key players within the ICT manufacturing or service industries. They are major sources of scientific and technological knowledge and related product innovations, and often provide decisive input to other (clusters of) companies such as specialized equipment suppliers. Many strategic R&D decisions of these firms exert significant impact on domestic and transnational patterns of scientific and technological activities, training and employment, as well related competitive performance of industrial sectors, regions and countries (e.g., Granstrand et al., 1993). Corporate commitment to basic research projects requires continuity in funding and a relatively stable institutional environment that can only be achieved by the larger multinational firms with a strong market position and a good prospect of a sustained presence in science-based industrial sectors. These large R&D-intensive companies are therefore characterized by: (a) extra funds for research, (b) producing or depending on science-based ICTs, (c) a commitment to broad-scope longer-term research objectives that may result in profit, and (d) internal management and research systems which enable publication of scientific results. Some of these firms tend to focus on in-house research, whereas others pursue strategies promoting scientific cooperation with other companies, public research institutes and universities.

Many of these large ICT enterprises are actors in the global arena. They tend to control their external technology transfers under the present circumstances of a severe global competition to maintain competitive in strategic areas. But at the same time they also face increasing internationalization of ICT manufacturing and R&D activities. Without proper localization in the various countries and markets difficulties might occur in the competition with the other global players on those ICT markets. Foreign direct investments by MNEs are therefore not only driven by the size of the market, regulatory regimes, the demand for dispersed R&D capabilities, but also access to scientific knowledge produced elsewhere. As for the latter, corporate R&D units need close interaction to exploit the benefits from existing forms of local knowledge as quickly and effectively as possible. These inputs may come as flows of codified or tacit knowledge, or related (in)tangible benefits, which are spreading as ‘knowledge spillovers’ from one research institution or scientific area to the next (e.g., Grupp, 1996). Shared know-how and these lines of personal interaction, often informal in character, are often key elements of such successful knowledge flows. Economic studies provide evidence of significant localization effects in research activities and in

[13] Several of the large MNEs are actually *industrial groups* comprising of a parent group or parent company and a range of (partially) owned subsidiaries and affiliations—both within the same country as well as abroad.

Table 5
Geographic and institutional distribution of collaborative research papers of large enterprises (home base), 1993–1996 (percentage of co-authorship links)[a,b]

	Intra-firm	External cooperation partners									
		Domestic		EU-15		USA		Japan		RoW	
		Public	Private	Public	Private	Public	Private	Public	Private	Public	Private
Computers and data processing											
European Union											
British Telecom	33	30	4	13	13	2	2		1	3	0
Siemens	14	43	9	9	4	6	2		2	10	1
Philips	10	43	17	8	8	3	4		3	3	1
Thomson	15	38	19	6	6	9	3		3		1
Alcatel	15	29	4	17	15	4	3	1		10	1
France Telecom	12	42	18	9	9		3			6	0
Ericsson	5	45	14	11	14	9	2				0
All firms ($n = 12$)	15	42	10	10	9	5	2		1	5	1
United States											
IBM	23	44	11	5	1			1	1	11	0
AT&T	34	38	13	5	1				1	8	1
Bell Communications	5	52	19	7	3				3	11	1
Motorola	22	48	22	2	1					2	1
Hewlett-Packard	8	46	27	7	2			1	2	6	1
Digital Equipment	4	47	16	20				2		10	0
General Electric	6	58	25	3					4	2	1
Texas Instruments	7	63	26							4	0
Hughes	4	70	20	2						4	0
Intel	6	69	13	9	2						0
Xerox	5	73	12	7						3	0
All firms ($n = 34$)	19	49	15	5	1				1	8	1
Japan											
NTT	47	22	7	4	3	9	4			5	1
Hitachi	60	15	13	3	1	4	3			1	0
NEC	30	39	13	5		5	2			4	0
Toshiba	32	21	28	1		5	10			2	1
Mitsubishi Electric	50	21	21	1		5	3				0
Matsushita	37	40	11			11				2	0
Sony	59	12	14	4		6				4	0
Fujitsu	19	36	17	9		6				13	0
All firms ($n = 16$)	39	28	16	3	1	6	3			3	0
Telecommunications											
European Union											
British Telecom	21	45	2	10	11	1	3		2	4	0
Alcatel	29	18	6	21	12	2	2	1	1	7	2
France Telecom	32	24	15	7	13		2			4	2
Siemens	14	46	6	10	14		1			8	0
Philips	7	37	12	19	21	4					0
Ericsson	10	27	13	16	20	5	1		3	3	2
KPN	2	30	12	23	25		3			2	3
All firms ($n = 12$)	18	32	8	15	15	2	2		2	6	2

Table 5 (continued)

	Intra-firm	External cooperation partners									
		Domestic		EU-15		USA		Japan		RoW	
		Public	Private	Public	Private	Public	Private	Public	Private	Public	Private
United States											
AT&T	55	22	14	3	2				1	4	0
Bell Communications	10	39	29	10	2				3	7	1
IBM	17	39	20	5	1					12	0
Hewlett-Packard	5	33	31	16	3			2		7	0
GTE	8	64	26		3						0
Motorola	16	53	19		5			2		2	0
Hughes	7	60	24							9	0
All firms ($n=30$)	32	34	20	4	2				1	5	0
Japan											
NTT	73	10	4	1	2	1	3			6	1
NEC	56	21	13	3	1		1			3	0
Hitachi	76	14	4		6						0
KDD	50	7	7				36				0
Fujitsu	18	29	12	18		12				12	0
Matsushita	46	29	8			4	13				0
Toshiba	41	29				18					12
Oki Electric	27	27	7		20					20	0
Mitsubishi Electric	40	40	15			5					0
All firms ($n=15$)	47	24	10	3	3	5	3			3	1

[a] Selection of firms per Triad region with the largest number of research papers (at least 30), sorted by descending frequency of publication output.
[b] See footnotes of Table 4 for an explanation of the types of external cooperation partners.

the spillovers associated with them (e.g., Jaffe, 1989). These geographical spillovers are more likely to accrue at ICT firms located near to research laboratories and universities.

The technology-driven motivations and long-term strategies of these firms force them to maintain their (downsized) central research laboratories and establish new laboratories abroad in order to effectively develop new forms of ICT research knowledge, and share and transfer information with their scientific partners. Many MNEs have now implemented technology-oriented strategies and investments aimed at establishing and maintaining these decentralized R&D laboratories across different countries. Furthermore, recent research by Hirst and Thompson (1996) suggests that multinational corporations are nowadays locating their R&D activities in countries and regions rich in knowledge and skills rather than those rich in cheap labor. It stands to reason that these foreign R&D laboratories will focus on local fields of expertise and scientific partners of local importance: not only for gaining access to the local science base and optimizing links with government-funded research, but also to attract high quality scientific and technical talent to provide a further source of new technologies and innovations that can be utilized internationally in their global network. In addition, results from a recent study on patenting by those foreign affiliates suggest that their foreign R&D activities are also driven by the need to provide technical support and applied research for production engineering and manufacturing in order to customize local products, materials and processes (Patel and Vega, 1998).

Table 1 already amply illustrated the importance of the corporate sector as a producer of ICT research papers. As described in Section 1.2, the participation of corporate researchers in scientific communities often requires public disclosure of research results, and encourages voluntary knowledge spillovers from industry to the public sector. Most of the research papers from the large corporations will originate from the central R&D laboratories that are primarily involved in goal-oriented fundamental research or applied research focused on technological applications. Additional research papers are sometimes produced by other corporate laboratories, such as distributed applied R&D facilities (divisional and applied research laboratories) or development centers that are more closely tied to production activities. Many of these foreign R&D units produce their own research papers in international journals, which occasionally list co-authors from other local research institutions. As a result, analyses of these firms' scientific co-publication partners not only offer empirical evidence of links with research partners within their home base, but also yields clues about the extent to which their foreign R&D units draw on knowledge and resources within local science and engineering bases.

Table 5a and b present the distribution of co-authorships for a set of large ICT corporations. The analysis covers 68 of the largest firms in terms of their scientific publication output. This selection includes all major R&D-intensive electronics and computer companies, as well as several large telecom operators, with corporate headquarters located in one of the Triad zones. About 80% of the research papers of the selected EU firms actually originate from their 'home country' (i.e., location of the headquarters of the parent group) often resulting from research conducted by central R&D laboratories. The majority of the other research papers by EU industry originate from laboratories linked to their subsidiaries and affiliates in other EU member states. The publication output of the selected American and Japanese firms appear to be less globalized: between 90 and 93% of their papers originate from the home country. It seems that Japan and the US appear to locate a smaller proportion of their basic research activities in other countries. Table 6a and b present the data for foreign affiliates of these MNEs.

Table 5a shows that, in the main, US firms take the lead over EU companies with regard to their propensity for partnerships within the respective national science bases—both with public research insti-

Table 6
Geographic distribution of collaborative research papers of MNEs foreign affiliates, 1993–1996 (percentage of co-authorship links)[a,b]

	Intra-firm	External cooperation partners									
		Domestic		EU-15		USA		Japan		RoW	
		Public	Private	Public	Private	Public	Private	Public	Private	Public	Private
Computers and data processing											
Siemens	9	52	19	4						15	1
Philips	9	45	23	5	5	4	1		3	4	
Thomson	10	17	14	5	3		1				50
Alcatel	3	46	6	15	18			3		9	
Ericsson	4	67	17			13					
IBM	31	36	7	4	1	16	3	1		1	1
Hewlett-Packard	3	41		31	10	7		3		3	
NEC	5	62	20	5				1		7	1
Telecommunications											
Philips	9	48	4	13	17	9					9
Alcatel	22	24	7	22	14			1	2	6	
Ericsson	5	38	21	14	14	2					
IBM	28	31	4	6		28	2			2	4
NEC	10	52	19	10				5		5	

[a]Affiliates located outside home country of the MNEs headquarters. Selection of firms whose foreign affiliates account for at least 20 research papers.
[b]See footnotes of Table 4 for an explanation of the types of external cooperation partners.

tutions as well as with other firms. As one might expect, the largest difference between the European firms and those in the US and Japan relate to the extensive intra-EU partnering of EU firms. These research partnerships of European firms are more or less equally divided across the public sector partners (10% of all their co-authorship linkages) and private sector partners (9%). The relatively small share of domestic inter-firm links (10%) is compensated by a relatively large fraction of inter-firm partnerships involving other EU member states. Totaling the shares of domestic cooperation and intra-EU cooperation adds up to a share of inter-firm linkages that is comparable to the situation in the US. The Japanese companies show a markedly different profile with a high propensity for cooperation among different research units of the same firm coupled to a relatively small fraction of papers involving cooperation with research performing institutions within the Japanese public sector.

These aggregate data provide a broad sketch of cooperation patterns that obscures the heterogeneity of the scientific partnership profiles of individual EU-based companies. At this level one can discern marked differences between these firms, reflecting corporate strategies and capabilities for scientific cooperation. British Telecom is characterized by a large number of papers involving researchers from different departments, whereas Ericsson seems much less involved in intra-firm scientific cooperation and more focused on research collaboration with other EU companies, and Alcatel's collaborative research activities show a preference for partners in the public research sector. Most of the EU and Japanese companies exhibit significant shares (5% or more) of research links with R&D partners based in the US.

Table 5b displays the scientific partner profiles of large firms with regard to their telecommunications-oriented research. The findings reveal a relatively large intra-EU input as compared to computers and data processing: 30% of the co-authorship links involve an organization from another EU member state (15% public sector and 15% firms). The stronger orientation on European partners is accompanied by lower levels of domestic collaboration, amounting to 40% of the co-authorships which is significantly less than in the area of computers and data processing (52%). There is also a slightly stronger tendency among EU firms to collaborate with US public research organizations (5%) as compared to the state of affairs in computers (2%). However, telecommunication research at EU firms shows a rather weak performance regarding intra-firm collaboration: only 18% of the co-authorships refer to research papers involving different R&D units, well below the scores of Japan (47%) and the US (32%). EU firms seem to rely more heavily on external collaborative research compared to their competitors in the US and Japan.

Summarizing these overall profiles provide empirical evidence that these selected large R&D-intensive companies and MNEs are (1) engaged in worldwide research activities, (2) rely heavily on in-house cooperation and networking, as well as (3) some external input from a geographically dispersed variety of public research institutes, universities and other enterprises. However, the core of the activities is still strongly focused on the domestic science base, which corroborates with other patent-based bibliometric findings indicating that R&D activities of MNEs remain to a large extent local (e.g., Patel and Pavitt, 1993). Both the US and Japanese firms show a strong reliance on their own in-house resources and those distributed throughout their national science base. EU firms seem to focus on their public national research system, but on top of that tap extensively into the resources of the EU member states, both through partnerships with public research institutions as well as other EU companies. The EU ICT companies thus seem more internationalized than either American or Japanese firms.

In conclusion, these findings indicate that the research activities of these large enterprises are certainly to some extent internationalized, both in terms of their substantive contribution to papers distributed through international scientific and technical journals, as well as their engage in international collaborative research. However, the results show little sign of fully-pledged globalization. The collaborative links are still predominantly focused on the local science base and the geographic distribution of foreign scientific partners appears is mainly confined to the Triad. Although the large MNEs exhibit this tendency toward 'Triadization' only a comparatively small fraction of their total publication output originates from their foreign R&D establishments. Hence from an R&D perspective these large multinational ICT enterprises still appear to a far cry from becoming truly 'stateless companies' which are characterized by (i) being active in many countries, (ii) cooperating with researchers around the globe, and (iii) tapping into knowledge and skills from those places and facilities where the best research is performed (Hicks et al., 1994).

3.4. Knowledge flows and spillovers: is EU scientific knowledge leaking away?

Viewed in economic terms, scientific information has intrinsic properties of a quasi-public good: it is re-useable and to a certain degree non-appropriable (non-exclusive), simultaneously accessible, possessed, and usable by others without loss of its intrinsic qualities (non-rival). Moreover, scientific knowledge that is codified in research papers is durable and can be transmitted at fairly low cost (Callon, 1994). The large R&D-intensive MNEs take advantage of these properties in their search for recognized sources of scientific excellence and new knowledge creation around the world. However, scientific knowledge is not intelligible and applicable by others without cost to the user. Companies that want to absorb and benefit from research performed elsewhere need complementary investments and accumulated capabilities (personnel, equipment, learning processes, and access to scientific networks) which can only be acquired by a strong presence in the global science base. MNEs with their own in-house research base and R&D laboratories are well-equipped to seek out and pinpoint knowledge and skills across the globe which might prove beneficial for achieving their medium or long term corporate R&D goals. Moreover, scientific knowledge is only partially non-exclusive which leads to external utilization and spillover effects outside the domain in which the knowledge was originally produced. Large R&D-intensive MNEs can take advantage of these knowledge spillovers by locating their foreign affiliates and R&D units in the proximity of knowledge intensive environments—such as universities, science parks, technopoles—in various countries they are able to tap directly tap into locally produced knowledge and use complementary assets (qualified scientists and engineers, specific R&D skills, technical facilities). [14]

As previously noted, a non-negligible fraction of the research papers that are produced by researchers working at large enterprises originate from their R&D units and affiliates outside the home country. Focusing on the selected large MNEs, the share of these papers amounts to 30% in the case of EU, 10% for Japan, and as much as 40% of the US research papers in computers and data processing (and 20% in telecommunications research). Table 6 displays the scientific partner profiles of foreign affiliates belonging to the MNEs with the largest publication output by their foreign R&D laboratories. The breakdown of their co-authored research papers presents further empirical insight into issues related to MNEs 'windows on foreign science' such as the decentralization of their R&D activities, corporate strategies on the use of scientific resources and related R&D networking, and spillovers from domestic research bases. It also enables us a glimpse of the kind of EU partners that non-EU MNEs prefer.

The data referring to computers and data processing indicate that most of these MNEs share a strong preference for linking up with partners in the national research systems, especially with the public research sector. In other cases, such as foreign affiliates of Alcatel and Hewlett-Packard, firms seem to have adopted a geographically broader collaboration strategy that incorporates partnering with organizations from other EU countries as well. Researchers at IBM's foreign affiliates co-author a considerable share of their papers with their colleagues based at

[14] There is an ongoing debate about the significance of foreign R&D units. The early literature stressed the role of home markets in determining firms' technological advantages. Successful export activities led on to the establishment of production facilities in other countries and any associated R&D activity was mainly concerned with adapting products to meet local tastes (Vernon, 1966). More recent analysis of the US patenting activity of the world's largest firms indicates that, for the majority, technology production remains close to the home base (Patel and Pavitt, 1995). Moreover, when these firms locate R&D activities abroad, no systematic relationship is found between their presence in a technical field and the relative technological strength of the host country in that area; there is no evidence of any relationship with the scientific strength of the host country in specific fields.

other IBM affiliates. As for the EU firms in telecommunications research, here one finds a stronger orientation toward partnerships with firms and with public sector institutions in other EU member states.

In brief, these patterns of co-authorship linkages indicate that the large R&D intensive firms are engaged in substantial levels of external scientific collaboration. Many of these firms appear to draw their basic scientific knowledge from a geographically dispersed set of actors. Nevertheless, localized effects tend to dominate ICT research cooperation—more than 90% of the partnerships involve local sources (i.e., research institutions from the same country or from other units within the corporation). Collaboration seems least localized in the case of EU telecommunications research where about 70% of the partners are based in the same country or in other EU member states.

Knowledge spillovers can be divided in tacit and codified knowledge. Tacit knowledge is often context-dependent and experience-based and therefore tends to remain invisible to external assessment. Codified knowledge however is concrete information and its flows can be traced and measured up to a certain degree (e.g., Grupp, 1996). Moreover, codified knowledge flows related to basic research leave a paper trail in the form of the reference lists of the research papers. These references to other papers indicate an awareness of research results which is primarily driven by the intrinsic value of the new knowledge for further application. These citation flows are also less constrained by cultural traditions, language, geographic proximity and institutional barriers, which tend to hamper person-embodied exchanges and transfers of tacit knowledge and affect partnering in (in)formal scientific cooperation arrangements. Hence, citations constitute a more unobtrusive reflection of the free circulation of knowledge, and are therefore suited for quantitative analyses of the direction and intensity of knowledge flows at the international frontiers of scientific research. These citation data enable a mapping of the interrelationships between the science bases of the EU, US and Japan in terms of their capability to produce relevant scientific results and their tendency to use knowledge produced elsewhere. Incoming and outgoing citation flows allow for a comparison of the relative importance of EU research for the EU itself,

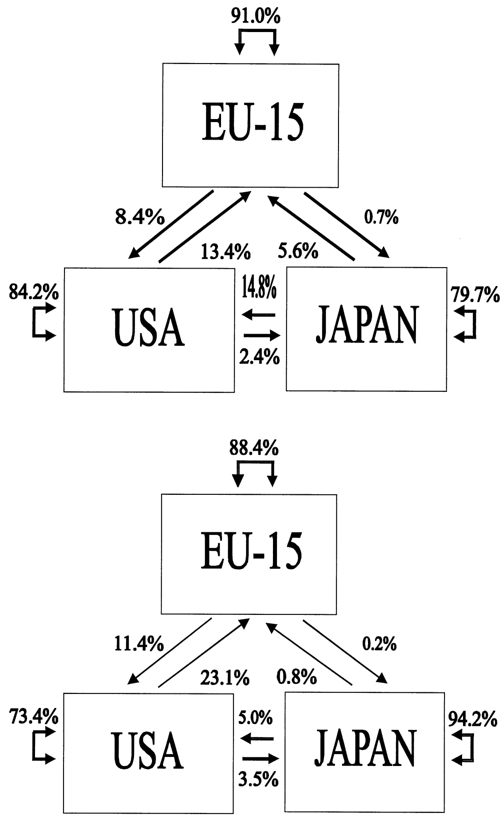

Fig. 1. (a) Intra-Triad citation flows in computers and data processing. (b) Intra-Triad citation flows in telecommunications. * Share of citations from papers in 1995–1996 to papers published after 1989.

as well as its appreciation by the US researchers and the Japanese. Significant imbalances between these flows are likely to indicate strong spillover effects. In the extreme case, one might even encounter excessive 'knowledge leakage' marked by very skewed citation flows.

Fig. 1 presents the pattern of international citation flows within the Triad in both ICT domains. The geographic distribution is based on the countries that were listed in the address heading of serial literature cited by ICT research papers in 1995–1996. [15] The

[15] Pertains to cited research papers published after 1989 and covered by the SCI. The number of citation links are based on a single counting scheme in which each pair of citing–cited countries is counted only once irrespective of the number of times the countries are listed in both author affiliations lists of the citing and cited paper.

large share of citations referring to domestic papers (i.e., originating from within the same Triad zone) is clearly the dominating factor in these knowledge flows. It accounts for as much as 91% of the EU citations in the domain of computers and data processing. Here one should take into account that these relatively large fractions are in part caused by author self-citations (researchers citing their previous SCI-covered publications), which in general amounts to about 15 to 20% of all citations. A relatively large share of the remaining EU references cites US research whereas only a minute fraction refers to Japanese science.

Basically, one would expect an inverse relationship between the size of the science base and its reliance of external sources of knowledge, where the US exhibits the strongest propensity to cite its own research output and Japan showing the smallest self-citation rate. Moreover, considering the sizes and the science bases involved and the free flow of citations, one might expect a balance between inflows and outflows. However, the expected relationship between size and citation flows does not materialize, primarily because EU research is attracting a relatively high proportion of the citations from the US: 13.4% of the US-given references related to EU science, whereas EU citations to US papers accounts for only 8.4% of the EU total. Considering the much larger number of US papers involved (see Table 1), this imbalance is much larger in terms of the absolute numbers of citations. This finding can of course also be taken as a confirmation of the high citation impact—and related scientific quality—of the EU science base (see Table 2), which in itself can be construed as a measure of its scientific success. On the other hand, the US researchers seem to be more interested and in need of EU research results than vice versa. These results suggest that EU knowledge is indeed to some extent leaking away to the US research and innovation system where is likely to be used there in related technological developments. The citation flows between the EU and Japan are characterized by the same pattern with a relatively large net negative ‘knowledge income’ for the EU. The citation flows in telecommunication research exhibit a similar general pattern of inter-Triad flows. In fact, the EU seems to be an even larger net exporter of knowledge to the US, which ties in with the excellent citation impact scores of the EU science base. The relationship between the size of the science based and citation flows in telecommunications research is quite the opposite of what one might expect. Note that the extremely high share of domestic citations in Japan—and to a lesser extent in the EU—might be explained by the stronger presence of a few (formerly) state-owned large telecommunication operators in the EU and Japanese science bases. These key actors tend to perpetuate a system dominated by long-standing institutional ties within domestic science systems and associated use of local knowledge and information flows.

Considering the differences in research environment and their main R&D objectives, one might expect differences in the pattern of citation flows between papers of industrial researchers and of those working in the public research sector. One may hypothesize that academic researchers are more embedded in the international scientific community and therefore more aware of relevant fundamental research outside the local or national science base. In contrast, industrial researchers and engineers seem more inclined to tap into local resources and rely on their knowledge generated within R&D networks and programmes in which they participate (Aloni, 1985; De Smet, 1992). Hence, one should expect more citations from industrial researchers to papers originating from the same Triad zone. In view of the presumably ineffective EU science–technology interface, one of the hallmarks of the perceived European Paradox, one may further assume that European industry is indeed impeded, and outperformed by the US, in its ability to optimally exploit scientific knowledge bases (in the EU and elsewhere). Hence, one may conjecture that EU industrial researchers are inclined to be more focused on their own science base—in contrast to a more outward orientation of their US counterparts.

The citation data by citing institutional sector presented in Table 7 seem to confirm these hypotheses for both ICT fields:

- The industrial researchers in the EU, USA and Japan exhibit a slight, albeit noticeable, preference for citing papers from domestic sources as compared to colleagues in the public sector. EU researchers show the strongest focus on the domestic science base.

Table 7
Intra-Triad citation flows broken down by citing institutional sector[a]

Citations from:	EU-15		USA		Japan	
	Public	Private	Public	Private	Public	Private
Computers and data processing						
Citations to:						
EU	90.1	95.6	14.0	11.5	9.4	1.7
USA	9.3	3.8	83.8	85.2	12.9	16.7
Japan	0.7	0.6	2.1	3.3	77.7	81.6
Telecommunications						
Citations to:						
EU	85.8	92.9	23.4	22.6	2.0	0.6
USA	14.0	7.1	72.5	74.7	12.0	3.8
Japan	0.3	0.0	4.1	2.8	86.0	95.5

[a]Share of citations (in %) from 1995 to 1996 papers given to previous research papers from 1990 onwards.

- US research appears to be much more significant to researchers at EU firms in comparison to papers originating from the Japanese science base (even though Japan has a high citation score in telecommunications research—see Table 2).
- The bias in favor of the local science base is somewhat stronger in the EU as compared to the US —the EU shows a 6% point difference between the public and private sector, the US only 2%. EU research activities in ICT industries therefore seem to be slightly more focused on relevant scientific achievements in their domestic and/or European knowledge base.

In summary, EU firms tend to be slightly less aware of relevant science outside the EU and are somewhat more inclined to cite local knowledge bases as an information source.

4. Concluding remarks

4.1. Evidence of the European Paradox

The range of bibliometric indicators adopted in this study depicts an EU science base that is predominantly characterized by its importance as a local source of basic research for EU countries. This applies to research in the area of computers and data processing as well telecommunications research. Europe seems to be using its local knowledge base to a considerable degree, thus casting some doubt on the existence a knowledge exploitation gap in the European science–technology interface. Given the numbers of co-authored research papers, corporate researchers appear to be quite actively involved in both domestic scientific cooperation as well as intra-EU collaborative linkages, and also collaborate with US institutions and firms. In doing so, these R&D-based corporations seem to have established many scientific links with major institutions in the public and corporate research sector. However, the results of the study also point out that Europe's ICT science base is characterized by a smaller fraction of research papers involving intra-firm cooperation (in both domains, but particularly in the case of telecommunications research), as well as a smaller fraction of public sector research papers resulting from internal cooperation (particularly in telecommunications). This may well relate to the fact that EU institutions and firms are usually smaller in size compared to their US counterparts, and may therefore lack the critical mass for such close collaborative links.

However, other findings emerging from this study exhibit features of the EU science base that seem to point more directly to the perceived European Paradox. Comparison with the scores of the US and Japanese science bases reveal the following tell-tail signs.

(1) High scientific quality of EU basic research in terms of international citation impact, particularly in telecommunications research. In fact, EU public research institutes top the citation ranking in both domains of fundamental research. EU firms are also well placed in both these rankings.

(2) Significantly lower shares of research papers by EU industry, particularly in computers and data processing.

(3) The EU science base appears to be a net exporter of scientific knowledge within the Triad, as indicated by a negative balance in citation flows in both ICT research domains.

In other words, ICT research in the EU appears to be at the international scientific frontier, but lacks a strong involvement of EU industry, and the resulting scientific knowledge appears to be extensively used by non-EU researchers as well. These observations indicate the presence of an exploitation gap within the EU science base and therefore lend some tentative empirical support to the assumption that European Paradox is indeed also rooted in European ICT research activities. However, there are some distinct differences between European research in the area of computers and data processing, and telecommunications research. The scientific performance of the EU science base in telecommunications is clearly superior to computers, and also seems to be more EU-oriented in terms of cooperation patterns—especially with regard to public–private linkages. It is more than likely that this can be in part attributed to the success of cooperation promoting R&D programmes of the European Commission in telecommunications such as ESPRIT which have encouraged the concentration and accumulation of research knowledge and competencies within EU-based firms, research institutions and R&D networks.

4.2. Policy issues

Scientific advances are clearly a major contributing factor in the long-term effectiveness of ICT innovation systems underpinning the production of marketable and commercially successful ICT products and services. Although direct relationships are hard to quantify, leading edge basic research and application-oriented research seem essential for the EU's strategic position in the ICT sector. Emerging ICT innovations will increasingly be based on a (re-)combination of scientific knowledge and technological know-how, and draw on research outputs and skills generated in collaborative networks that will most likely become increasingly international in the foreseeable future. EU nations will therefore require a sustained strong ICT science base to be able to effectively access and utilize that global pool of knowledge, skills and artefacts. The findings of this study indicate that the necessary knowledge infrastructure for basic research seems to be performing quite well in terms of knowledge production and international scientific impact.

A considerable number of private sector institutions in the EU—and some of the large R&D intensive enterprises in particular—have been producing significant numbers of research papers in this decade in international scientific and technical journals. Clearly, many firms and private R&D laboratories are contributing significantly to our publicly available, new scientific knowledge. As such, they are clearly a decisive input to the ICT science base and deserve more credit than merely being considered as 'free riders' whose main objective is to exploit the large reservoir of research results generated by universities and other public research laboratories.

As regards to EU knowledge transfer from the public sector to the corporate sector, previous R&D policy studies have pointed out that proximity is an important factor in forging research linkages. It has become apparent that language barriers and tacit components of knowledge can be major obstacles in communication and knowledge diffusion processes. Firms that are geographically and culturally close to research institutions are therefore better placed to reap benefits of research outputs (Dasgupta and David, 1994; Pavitt, 1994). This 'home advantage' of EU firms in the EU science base is quite visible in the research papers. The large share of public–private co-authorships by EU firms provides convincing empirical evidence of the important role of domestic science bases for knowledge transfer, and also indicate a relatively strong intra-EU cooperative research network facilitating these cross-sectoral linkages.

The bibliometric data in this study also provide ample evidence of transnational cooperation—both within and between institutional sectors—and point out that foreign affiliates of MNEs are tapping into domestic science bases. Here one must keep in mind that the ICT industry has been globally oriented for several decades now: many large electronics firms have been operating on a global scale from the very beginning. Yet, comparatively few signs are found of true globalization in R&D activity in the private sector in terms of decentralization of basic research facilities and related output of scientific papers. However, in view of the previously noted market pressures on ICT firms and the trend towards further internationalization of manufacturing and marketing activities within ICT industries, it is not unlikely that the future will not only bring us more foreign R&D units as well as an increasing number of R&D intensive ICT enterprises forging international cooperative links and entering technological alliances to limit the risks and costs involved in leading edge ICT R&D. This new way of operating will rely on building and sustaining more links between scientific knowledge producers and those involved in knowledge application—on the regional, national as well as global level. Customized research partnerships and outsourcing arrangements are likely to become an essential part of developing and managing dynamic R&D networks and technological alliances as assets that enable firms to accrue the wider benefits of the global ICT science base. These global R&D strategies will also require intensified coordination in order to allocate the scarce high-quality resources efficiently and effectively.

Globalization and localization are not only an important factor in decisions regarding manufacturing and R&D management of ICT enterprises, but also in technology-related economic policy by many governments. It is argued that local S&T infrastructures determine the capacity for advances in ICT R&D and shape specialized domestic patterns of ICT innovation activity and enhance competitiveness.[16] Domestic and local advantages in specific places include formal links between university research and industrial R&D as the outcome of cumulative investments in human and technological capabilities. These strengths in research areas can also be crucial factor in attracting foreign ICT companies to fund and carry out R&D. Advanced industrialized countries and regions are therefore keen to strengthen their domestic ICT sector by promoting the transfer of knowledge and skills generated in their national research base to local ICT service and manufacturing industries. R&D policies should therefore support both local capabilities in public research and the ability of firms to form links with public research outside the home country or even outside the EU. The strong proximity effect could be a problem in the ICT sector where the US and Japan have competitive advantages, and tend to find information sources in their own regions to be more important. However, policies aimed at encouraging European firms to form alliances with American and Japanese research institutions and establish joint ventures with foreign firms could help to bridge this knowledge gap.

However, it is important to note that future benefits of (supra-)national governments' investments in ICT research are not likely to be fully captured by knowledge producers—neither by the local or domestic science base, nor the regional or national economies involved—but will also be transferred, exchanged and exploited elsewhere. Such spillover effects are inevitable given the internationalization of ICT firms in knowledge-based economies and the ongoing process towards further scientific and technological cooperation. Knowledge and skills are slowly becoming less and less reliant on traditional institutional frameworks or geographical locality. Time will tell whether or not the EU will be a net beneficiary or supplier of scientific knowledge in the near future. Given the outcome of our analyses, which provide a first approximate that more knowledge seems to be flowing out of the EU than inwards, it is not unreasonable to assume that the internationalization in ICT industries and related science bases might actually exacerbate this 'leakage'.

4.3. Towards a benchmarking of the EU ICT science base

This exploratory case study of the European Paradox in the ICT science base focused specifically on the stock and flows of scientific knowledge as embodied by research papers published in the international scientific and technical literature. This so-called 'bibliometric' approach provides a set of measures and statistics which enables systemic and objective comparisons at various levels of aggregation and across a range of features including research output, cooperation and knowledge flows. These bibliometric indicators provide relevant and objective data about linkage patterns and institutional features underpinning the workings and dynamics of the entire science base. Results of bibliometric studies can be incorporated into large-scale comparative assessments of the scientific performance of EU as a whole, its member states, R&D intensive regions or major R&D institutions.

It goes without saying that this approach is bound to give an incomplete picture of scientific strengths

[16] Feldman and Florida (1994) argue: ''In the modern economy, locational advantage in the capacity to innovate is ever more dependent on the agglomerations of specialised skills, knowledge, institutions, and resources that make up an underlying technological infrastructure.''

and weaknesses. Bibliometric data are by definition retrospective: research papers, and citations to those papers, refer to R&D activities of the past. This inherent limitation obviously restricts the scope for assessments of the current state of affairs in ICT research or of future developments. Nonetheless, these data still represent relevant information given the cumulative nature of knowledge production which builds largely on prior (supra)national research capabilities and R&D infrastructures: the past performance is often the best predictor of scientific achievements and developments in the near future. Bibliometric indicators can provide valuable background data for tracking trends, and monitoring new features in the EU ICT science base.

In conclusion, bibliometrics provides a useful analytical framework for objective quantitative analyses of phenomena such as the European Paradox from the perspective of printed scientific outputs. As such it may help lay empirical foundations for further science policy analysis and debate in the EU (e.g., Gabolde, 1998). Clearly, further research is required to fully assess the added value of all the bibliometric results presented in this paper. A comparison with (quantifiable) information derived from other independent sources, such as EU-wide surveys like the Community Innovation Survey (CIS) or sectoral studies of research cooperation, patenting and technological networks in ICT industries, should provide interesting material for verification and might also pave the way for benchmarking studies of ICT science–technology interfaces within the framework of the EU research and innovation system.

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