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Is the commercialisation of scientific research affecting the production of public knowledge? Global trends in the output of corporate research articles

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Abstract

Judging by the large R&D-active companies that have slimmed down their research labs in recent years, it would seem that corporate research is increasingly managed as an economic asset that is predominantly driven by market forces and ruled by IPR strategies. Has this development significantly affected industry's basic research and interactions with research communities in the public sector? This paper examines the global trends in an underdeveloped source of information on corporate science: their research articles published in the international scientific and technical journals.

Statistical analysis of some 290,000 corporate research articles published in 1996–2001 indicate that, contrary to large increases in patenting and growth in patent citations to research literature, the numbers of research articles that list author affiliate addresses in the corporate sector have declined steadily, especially for those articles authored exclusively by industrial researchers. More detailed analysis of trends in the bio-pharmaceuticals sector and semiconductors sector show sector-specific publication trends and patterns related to specifics of their innovation processes.

Overall, these observations provide factual evidence indicating that corporate research is in an on-going process of structural change characterised by a stronger emphasis on the appropriation and commercialisation of in-house research results.

Keywords: Corporate research; Research partnerships; Knowledge protection and dissemination; Bio-pharmaceuticals; Semiconductors

1. Introduction

This paper is framed in the resource-based view of the firm. Among the many resource-related factors that influence a firm's organisational competitive advantages and business performance is its ability to innovate, to improve existing processes and products, and to produce new goods and services for the marketplace (Barney, 1991). The realization of the firm's primary role as a knowledge creator[1], as well as knowledge applicator, has led to knowledge-based theories of the

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[1] Conceptually speaking, "knowledge" is defined as a relational, interpretive structure to process and understand a diversity of concrete data and other types of information such as tacit experience and skills. Knowledge represents a synthesised aggregate of information, deriving its meaning from information and vice versa. In practice, "knowledge" and "information" have fuzzy boundaries and are used interchangeably. For ease of reading, this paper will adopt the unifying word "knowledge" to denote both concepts.

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firm (Grant, 1995), where R&D-intensive technology companies generate, accumulate and apply scientific and technical knowledge to produce incremental or breakthrough technological innovations. The intricate relationship between investments in scientific research, technological development, tacit knowledge resources, and technological innovations is generally recognized to be an important driver of the competitive advantage of those firms. There is empirical evidence that a firm's R&D efforts may directly improve its ability to innovate (Griliches, 1979), and indirectly help the company to absorb outside knowledge (Cohen and Levinthal, 1990), both of which having a profound impact on its productivity (Hall, 1996). The research base is acknowledged to be a critical element of a firm's innovation capability that is fed by continuous interaction with external information sources such as universities and other public research institutions. Empirical studies have shown that many corporate technical inventions and related innovations depend upon external scientific progress (Mansfield, 1991, 1995; Beise and Stahl, 1999; Tijssen, 2002).

Traditionally, the creation of scientific knowledge and associated technical know-how was viewed as a linear process in which firms endogenously seek out and apply these knowledge inputs, in the form of R&D efforts, to generate commercially valuable innovative output. Recent developments in evolutionary economics view this process as the outcome of context- and firm-specific learning processes that bring in their pre-existing competencies, experience and knowledge (David and Foray, 1995). The linkages and interactions among the economic agents who produce, diffuse and adopt this knowledge are seen as crucial for the commercialisation of knowledge inputs into innovative outputs. The "distributive power" of a company (a concept introduced by David and Foray) within innovation systems, has become key for staying competitive.

Owing to this interactive and semi-open knowledge creation system, the same firms that produce the knowledge do not always appropriate the expected returns of their R&D efforts. Voluntary knowledge transfers or involuntary spillovers of scientific and technical knowledge may be absorbed and utilized by other firms, especially in the case of exploratory scientific and technical research. R&D-active firms therefore face the problem of effectively balancing the production, protection and dissemination of their research-based knowledge.

This article presents results of an empirical study of world-wide quantitative data on corporate research outputs, suggesting that the balance is shifting in favour of knowledge protection and appropriation, rather than production and dissemination. Section 2 elaborates on the relevant concepts and economic issues associated with this "knowledge flow balance" in the corporate research sector. Section 3 describes the main features of the information sources and analytical methods. The main findings are presented in Section 4, followed by tentative conclusions and some cautionary remarks in the final section.

2. Knowledge appropriation and knowledge spillovers

2.1. Corporate basic research: life-blood or bleeder?

After the golden age in the 1960s and 1970s, and following the cutbacks and short-lived upswing in corporate science spending in the late 1980s and early 1990s (e.g. Rosenberg, 1990), a gradual re-orientation of business strategies and IPR policies took off in the mid 1990s when industrial research labs became "leaner and meaner". Labs became smaller, more de-centralised, and their scientific and business performance more closely linked to corporate strategic planning and investor confidence. Many of those structural changes started either in Japan or the United States. Researchers and engineers in the labs were made more accountable for their actions and research outputs, including material for research articles published in the journal literature (Buderi, 2000a; Varma, 2000). Further empirical evidence indicates that this evolution in the industrial research landscape is still ongoing: companies have prioritised R&D to stay competitive on the long run, but at the same time many large firms have downsized their central research labs (Coombs and Georghiou, 2002).[2] As a result,

[2] The central laboratories tend to perform the "core research" serving the whole enterprise, especially "basic" core research with a longer-term objective. However, application-oriented core research may also be attached to production units or in the case of multinational companies the central units in different countries.

industrial research now seems to be more than ever driven by new business creation and the commercialisation of research outcomes into marketable products, processes and services. As the introduction of new products has increased vastly and lead times have diminished, corporate research endeavours are now also assessed and evaluated continuously in terms of quality, productivity and (potential for) value creation.

Faced with increasing competition and shorter development cycles, companies' innovation strategies include collaboration with major sources of new knowledge creation around the world. This is most marked in the new research-intensive sectors like biotechnology where the underlying science is extremely dynamic, the technologies are strongly science-related and the development often takes place at the interface between different disciplines and fields. Knowledge derived from scientific research or engineering research provides an invaluable understanding and theoretical base for those innovation-oriented corporate R&D activities. The benefits of research are derived not only from in-house applied research, but also from basic research (Mansfield, 1981; Griliches, 1986). Basic research is usually a costly activity with uncertain strategic benefits or monetary gains and has therefore always been a small part of corporate R&D—on average some 10% of the business R&D expenditures are devoted to research with a long-term orientation, which is traditionally confined to the large R&D-active technology companies and their central laboratories. An increasingly large share of the funding for those laboratories now comes from business groups and product divisions through contractual agreements about programs and costs, a fraction ranging up to an estimated 75% in the case of the large US companies (Larson, 2001). Since many of the science-intensive companies are now operating in rapidly changing technology areas and markets, the term "basic research" is often no longer appropriate.[3] Long-term research projects are often reduced to schedules of no more than 2 or 3 years, where corporate research portfolio's now balance short-term deliverables with long-term objectives. The largest firms have developed various organisational and management models to balance the needs of business groups and the R&D agenda of the central research laboratories (Buderi, 2000b).

This process of "marketisation" of corporate research places a stronger emphasis on protection of research findings and exploitation of intellectual property rights, especially in the case of findings of (potential) commercial or strategic value. Once scientific or technical information is disseminated intentionally (or spilt over unintentionally) into the public domain competitors are free to benefit. In fact, one may argue that firms ought to perform only the most essential basic research, closely guard valuable results, and commercialise it rather than making it public through publications or otherwise. Hence, why do firms still bother to invest in longer-term research when those large expenditures and commercial risks may outweigh business advantages? More importantly for this study, why should corporate researchers still want to publish their findings in the open literature? Providing answers to these questions requires further examination of the economic relevance of corporate knowledge bases, the role of scientific and technical research in absorbing relevant knowledge, and intricate relationships between knowledge appropriation strategies and dissemination practices.

2.2. Knowledge bases and absorptive capacity

Mainstream economic theory considers scientific knowledge a uniformly available public good that can be transferred and learnt at little cost. Non-appropriability and indivisibility of knowledge, coupled with inherent uncertainty as to the results of basic research, to were supposed to lead to under-investment by firms in basic science (Nelson, 1959; Arrow, 1962). True enough, cutting-edge basic research tends to be expensive and risky, and once results are written down ("codified") and made publicly available every company can enjoy the knowledge

Applied research of a more ad hoc nature, can also be carried out in an operational department such as in an industrial design department, quality control department of production department.

[3] Industrial basic research, loosely defined as research not related to current corporate products, covers both longer term scientific research and engineering research. This kind of research is often driven by a strategic vision of the market with a 3–5 year time horizon. In certain fast moving technology areas, the terms "research" and "long-term" are no longer coupled in the traditional way; the commitment to research is long-term, but the research projects and programmes themselves may have short term objectives and deliverables.

freely. Firms may therefore be reluctant to invest since knowledge may to spillover easily from first-movers and innovating firms to other firms that can free ride on the efforts of the innovators. Hence, firms have relatively little incentives to engage in basic research, or so it is argued. Several researchers have questioned whether spillovers of valuable knowledge occur as easily as portrayed by Nelson and Arrow. Economic research in the 1980s and 1990s have challenged these assumptions and concluded that firms require an appropriate knowledge base[4], and need to perform their own basic research in order to absorb and appropriate 'free' scientific information and technical know-how (Mowery, 1983).

Knowledge creation based on scientific and technical information is a complex and cumulative process. For firms to absorb and assimilate codified scientific and technical knowledge requires a certain measure of learning-by-doing and support by appropriate levels of tacit knowledge (Nelson, 1989; Pavitt, 1991). Firms need a research base—either in-house or externally—which covers all resources from which new scientific and engineering knowledge can be drawn. To do so, the intensity and effectiveness of these research-related interactions is determined to a large extent by the firms' own commitment in learning activities and the ability of firms to recognise and appreciate the value of new, external information (ranging from generic science to new production equipment), to assimilate it, and exploit its economic potential through commercialisation. Cohen and Levinthal (1989, 1990) have labelled this ability the "absorptive capacity" of the firm, and argue that especially when learning is difficult, a firm's ability to internalise, modify and apply external basic research for its own commercial gain is a function of its R&D investment. Given that learning is a highly localised and history-dependent process, the current set of skills and expertise owned by a company are critical for the nature and direction of learning processes that aim to enhance the knowledge base of the company in the future. Hence, the ability of a firm to use the results of research efforts made by other firms, or other public research organisations, is contingent on its ability to understand them and to assess their economic potential, an ability affected by the size of a company and its access to complementary assets (Levin et al., 1987; Teece, 1987). Thus, although scientific information is indeed cheap to transmit and re-use (but often very costly to produce), the capacity to understand, interpret, modify, extend and apply that information requires an extensive knowledge infrastructure, networks and equipment. These institutions and facilities are very expensive, especially if one wants to keep abreast of the results of leading edge research and participate at the frontiers of international science. Lack of tangible or intangible investments (in the form of human capital) in a relevant area of expertise early on may therefore inhibit the development of technological knowledge and innovations by the company in that area at a later stage. The optimum level of internally-generated research knowledge and skills versus externally sourced knowledge and technologies, and the related optimum level of protection versus publication of internally-generated knowledge, will depend on the strategy and level of development of the firm. However, all firms are users of the existing stock of knowledge, whatever the flow into that stock for which they are responsible. So even for the most developed and sophisticated firms, absorptive capacity will remain significant.

2.3. Co-operation, networking and knowledge flows

The most effective way for companies to evaluate and monitor key outcomes of their in-house research, and assess the potential of external research, is to be an active participant in research communities—either locally, domestic, or on the global level. However, the private sector engages in scientific research only when expected private returns from it rise above a minimum level. Obviously, the business sector has always been engaged in scientific research primarily out of self-interest. Moreover, in-house R&D efforts alone

[4] A company's knowledge base comprises of the accumulated sum of knowledge on which the advance of a company relies—including not only codified knowledge, but also tacit knowledge and knowledge embedded in equipments, instruments, production plants and organisational structures and management routines. The former refers to knowledge that has been reduced to a written and transmittable form, while the latter refers to knowledge that exists (sub)consciously in the human mind, is acquired through experience, imitation, and observation, and can be transferred only by personal contact (David and Foray, 1995; Nonaka and Takeuchi, 1995).

might no longer able to create enough economic value to warrant large expenditures in basic research given the uncertain outcomes of exploratory scientific and engineering research. In order to reap economies of scale and scope beyond the reach of a single company, or to off-set their own slimmed-down corporate research programs, many large R&D-active technology firms have increasingly turned to outsourcing and sub-contracting long-term research to universities, or are now engaged in joint research ventures, thus creating a new "industrial ecology" of corporate R&D (Coombs and Georghiou, 2002), where the public sector research has become a major source of new scientific knowledge and advanced technical skills through various diffusion channels (Salter and Martin, 2001).

Firms that are in the business of developing new products are more likely to find public research to be an important source of information than firms that innovate in order to improve their existing products (Arundel and Garrelfs, 1997). Many large R&D-based companies have forged stronger informal relationships and formal (contract-based) linkages with public sector research organisations, and industry now largely relies on universities and research institutes to explore of new avenues of research and generation of new knowledge (Meyer-Kramer and Schmoch, 1998). OECD data confirm this trend, indicating that larger shares of corporate funding for basic research are being spent on joint ventures with external research partners, especially within the local or domestic university sector.[5] Indeed, several large bio-pharmaceuticals companies, like Pharmacia, Syngenta and Amgen, have closed multi-million dollar deals in the late 1990s with US universities to obtain (exclusive) access to results of frontier basic research.

The nature of the knowledge-generation process itself seems to be evolving towards a more network-embedded process with a stronger emphasis on the interplay between knowledge-demand and knowledge-supply, as well as increased levels of transdisciplinarity of the research projects, and a larger degree of heterogeneity of the actors involved (Gibbons et al., 1994). This pervasive development can be seen in the rise of institutionalised co-operative structures such as inter-firm joint research ventures and university-industry strategic research partnerships (Hagedoorn et al., 2000). By transforming industrial R&D problems into research topics for basic research, many public–private research partnerships and joint research ventures benefit the research agenda's of academic researchers and engineers. Hence, the connection to academic science and scientific networks shapes both scientific advances and technological progress.

The emphasis on access to external sources, and the view of knowledge as the outcome of interactive learning processes, implies the existence of knowledge flows that link different sources of new scientific and technological information and its potential users. These flows of know-how and information include voluntary dissemination, intentional transfers, as well as accidental or unintended spillovers. There are many communication channels and routes for these knowledge flows to materialise. For example, Cockburn and Henderson (1998), building on Cohen and Levinthal's notion of absorptive capacity, suggest that the degree to which firms are connected to universities is an important factor for utilising those external knowledge flows. The general findings from their research suggest that three major types of connections and modes for knowledge flows exist: (1) research publications and co-authorships; (2) proximity to star scientists; and (3) human resource movements. In the following we will focus on linkages and flows embodied in research publications to describe recent world-wide output trends within an increasingly 'networked' system of corporate basic research.

2.4. Corporate research papers in the open literature

Research labs of firms have to deal with the trade-off between sharing and protecting scientific information. On the one hand, publishing research findings in the scientific literature would seem very much at odds with industry's tendency to privatise scientific and technological knowledge. Obviously, in many instances it is in the self-interest of industrial actors not to publish since that could be beneficial for their competitors. Industrial researchers and engineers would seem to have little incentive to disseminate results of pro-

[5] The fraction of business funding in the OECD countries of research conducted in the university sector has increased from 1.4% of the total business R&D funding to 1.7% during the years 1995–1999 (OECD, 2000).

prietary research that might be interesting and helpful to outsiders. On the other hand, each year many thousands of research documents related to, or directly originating from industrial research, do become public knowledge. In fact, more than 10,000 research articles alone are published annually in international scientific and technical journals (see Section 4). Clearly, writing publications for these peer-reviewed journals costs valuable time and corporate money whereas the commercial benefits would seem uncertain or are sometimes marginally at best. So why do industrial research labs act as quasi-academic research labs and publish these large quantities of papers?

Nelson (1990) argued that firms have many good reasons to publish (selected) results of their research endeavours of low competitive value: to maximise visibility and link up to the scientific community, but also to establish intellectual claims and legal rights.[6] Hicks (1995) points out that the corporate research papers in the open literature may also signal R&D capabilities to (potential) partners and suppliers. Additional incentives of more recent data include R&D management objectives such as: attracting private capital and public research funding, and gaining a reputation and enhanced credibility for doing high quality (basic) research in order to attract first-rate researchers and technicians. As such, publications not only represent the firm's production of scientific and technical knowledge as a public good, but also act as PR vehicle and as a gateway in a two-directional knowledge diffusion pathway between the firm and scientific communities the outside world: in the case of low rivalry conditions, firms may expect reciprocity exchange effects where publications may induce further research by others.[7] This "open science" mechanism produces a pool of knowledge that can be used freely by the international scientific community from which corporate researchers draw very heavily (Jaffe, 1989).

Naturally, companies will tend to publish only a fraction of their research findings that are of interest to the relevant scientific and engineering research communities. Firms will carefully balance their desire for secrecy and their willingness to share and disseminate information. It will usually be decided to keep (potentially) valuable information in-house, and only by exception will a more open publication policy be enforced in which some key information is shared or exchanged. The latter will involve the screening of manuscripts and partial dissemination of research results, imposing strict conditions on accessing research material and outcomes, and enforcing of delays in publication. Given the strategic nature of industrial research and the importance of intellectual property rights, these publications should therefore mainly be seen in the light of corporate business strategies. Zucker et al. (1998) asked how a firm's linkages to scientific networks affect its overall economic performance and more specifically its technological progress, particularly in instances when novel technologies are science-based. With respect to the role of research publications in these linkages, respondents indicated that especially in periods when there is a shift in technological paradigm to one closely linked to science, publications by the leading firms are crucial for mobilising relevant in-house research and external research to make a successful transition.

Whatever explains corporate scientific publishing, it is obvious that publishing is not the main purpose of industrial researchers and engineers, and firms publish much less research articles than comparable public sector institutions (universities, research institutes and government laboratories) with the same volume

[6] The rule of "scientific priority" in the scientific communication process identifies the prime knowledge producer and the moment of publication and builds a reputation, which is crucial for obtaining recognition in the scientific community, receiving tenure, entering networks and receiving grants. Granting researchers authorships and associated 'moral' intellectual property rights of their fruits of labour, rather than granting them exclusive intellectual rights to the knowledge, resolves with the "knowledge market dilemma", where researchers need to be efficient and productive in their research efforts while having little or no chance of keeping the financial rewards for themselves. It enables the creation of a private asset for the 'discoverer' resulting from the very fact of giving up exclusive rights. The need to be identified and recognized as the discoverer impels the speedy and full disclosure (Dagupta and David, 1994). This reward mechanism creates races or competitions, still involving full release of the knowledge. Full disclosure also acts as a quality control system since publicly published results can be duplicated and checked by other scientists. The rule of priority combined with the open science system guarantees dissemination without reducing motivation, while improving the quality of research and cumulative and collective scientific advance.

[7] Similar reasons may exist for companies to reveal (research-based) innovation-related information (see e.g. Harhoff et al., 2000).

of research resources and working in the same fields of science. Moreover, if firms do decide to publish, many of these papers are likely to be co-authored with researchers in the public sector. In the case of joint research partnerships with public sector organisations, the corporate sector is also bound to apply slightly less restrictive strategies in view of their partner's dissemination-oriented research missions, their incentive structures and their IPR policies. Companies are therefore often willing to tolerate some measure of (informal) spillovers from their academic partners to the scientific community. Corporate sponsors of public research engaged in contract-based ("formal") co-operation will often negotiate the first rights (of refusal) to the fruits of research and the scientists must delay publishing to allow companies a head start for commercialising through filing for patents or by other means.[8] Scientific co-operation with public research organisations on a more "informal" personal basis are more likely to generate jointly authored research papers, especially in the case of academic partners who have strong incentives to publish results related to research sponsored by industry, or conducted in co-operation with corporate sector. Irrespective of the nature of contractual agreements, in the process of producing these co-authored scientific papers, researchers are likely to exchange tacit and embodied elements of knowledge and skills.[9] These co-authored research papers therefore not only gauge the production of new collective knowledge, but also the absorption of external knowledge by the company during knowledge creation and codification processes.

In most areas of international open science, the main channel of disclosure of codified knowledge is that of conference proceedings or research articles published the quality-controlled peer-reviewed international scientific and technical journals. The next section turns to the further introduction of the latter type of research publication.

3. Information sources and methodology

3.1. Bibliometric analysis of corporate basic research

General trends in the output of basic research efforts within large science-intensive technology firms, or for that matter entire science-based industries, can be gauged from statistical analyses of the quantity of papers published in international peer-reviewed scientific and technical journals. This literature-based ("bibliometric") approach produces a large body of quantitative data that provides a statistically robust frame of reference for analysing the changing contribution of the corporate sector in research communities. These data enable comparisons between (parent) companies, while aggregation of those firm-level data allow for comparisons between associated industrial sectors. The view taken in this study is that the analysis of joint publications provides complementary statistical information to that provided by surveys of industrial sectors, regions or countries. The numbers of co-authored papers originating from (informal) joint research ventures—either intra-firm, inter-firm and public–private—enables a range of statistical analyses on the volume and composition of co-operative corporate basic research. The underlying assumption is that co-publication data are a reasonably good, albeit partial, indicator of collaborative research activity—and co-operation-based knowledge flows and exchange—their main advantage being that quantitative information is available (over time) for specified firms and their (primary) business sectors, as well as related scientific fields. However, bibliometric statistics and indicators should be handled with due care as a reliable source of conclusive empirical evidence on actual scientific co-operation (Katz and Martin, 1997). For instance, our database contains several journal articles listing 10 companies or more in the author list; content analysis of these "corporate research network" papers indicates that these papers are in fact meant to formalise and disseminate scientific or technical standards (e.g. protocols for clinical trials) rather than results of joint scientific research activities.

[8] One of the main arguments for patenting of the results of basic science is that in many cases the absence of protection will deter any economic use of these ideas, that is commercial applications at industrial scale by business enterprises. Implementing a scientific discovery or idea requires substantial R&D investments that business enterprises will be ready to make if they have access to the knowledge on an exclusive basis. With no protection, such as patents or exclusive patent licensing contracts, investors will not feel immune from knowledge spill-overs and imitation, which will add to uncertainly and deter any such venture.

[9] These informal contacts are also likely to include the transfer of additional tacit or codified non-published information to companies (e.g. Cohen et al., 2002).

Bibliometric studies of corporate publication output in international journals conducted as early as the 1970s have provided empirical data on trends in the publication output in the 1980s up until the mid 1990s, especially for the US industry (e.g. Small and Greenlee, 1977; Halperin and Chakrabarti, 1987). The findings revealed significant increases in the 1980s and early 1990s, resulting in a 5–10% share of the corporate sector in the global scientific output. Several studies have focused on large firms, a single industry, or the distribution over papers across industrial sectors within one country (e.g. Hicks et al., 1994; Godin, 1996; Tijssen et al., 1996; Hicks and Katz, 1997). However, in spite of the growing policy interest there have been to my knowledge no attempts to gather systemic data to analyse the nature and extent of world-wide output levels and trends at the level of industrial sectors and countries.

Returning to the major socio-economic forces impacting upon basic research and publication strategies of modern-day industrial researchers (i.e. the three "C"s: Competitiveness, Co-operation, and Commercialisation), the aggregate-level bibliometric data on their research papers in international journals allow us to address the following sets of key questions:

1. To what extent have the competitive pressures in the 1990s forced science-based industries to commercialise their research efforts and to shift their focus from being a 'science-performing industry' towards operating as a 'science-using industry'? More specifically, has the published research output of the corporate sector dropped, and has the number of co-authored research papers increased at the same time?
2. How has this re-orientation impacted to co-operative research ventures of firms, especially those with other firms—as opposed to partnerships with public sector research institutes and universities? In other words, has the share and composition of jointly authored corporate research papers changed?
3. And to which extent are the observed trends sector-specific? Do we find different trends in the major science-based industries?

3.2. Databases and definitions

Providing answers to the above questions requires a comprehensive database of corporate research papers covering all industrial relevant fields of science, and the major research-base firms and industrial sectors. The bibliometric study presented in this paper is restricted to the internationally visible production of corporate research papers covered by the large multidisciplinary bibliographic databases compiled by Thomson-ISI. These ISI databases, especially the Science Citation Index®, and the web-based version Web of Science®, provide the best source of information to identify the basic research activity across all countries and fields of science. The statistical analyses were done with CWTS's tailored version of the Thomson-ISI databases. The research papers include all document types that, in varying degrees, originate from original basic research: research articles, review articles, research notes, and letters (editorials, book reviews, etc. are omitted). The vast majority of those papers are research articles. CWTS assigns each paper in its database only to those (main) organisations where the address information refers unmistakably to the respective organisation.[10]

The analysis covers all research papers listing at least one author affiliate address referring to an organisation that CWTS classified as belonging to the "corporate sector". The demarcation of this sector follows the OECD definition: "all business enterprises, organisations and institutions whose primary activity is the commercial production of goods and services (other than higher education and medical care) for sale to the general public at an economically significant price." This institutional delineation includes public enterprises, public–private consortia, private non-profit in-

[10] CWTS has developed a thesaurus of company names based on a (semi-)computerized routine to identify research papers that list private sector organizations. This routine scans the information on the affiliate addresses of authors listed in the bibliographic records. The current version of the database includes some 40,000 different main organisations assigned to the private sector, the vast majority of which are business enterprises. All large science-based companies with substantial publication outputs are included. The number is a lower bound since private sector organisations are only included if: (1) their name in the address includes an acronym in the suffix or prefix indicating their official legal status (Inc., Ltd., GmbH, etc.), and/or (2) they are identified as a for-profit business in other sources (mainly websites or the Dun & Bradstreet database). The "error rate" of this categorization—in terms of "missing" non-coded cases of business companies—cannot be determined due to lack of decisive information, which is especially the case for very small companies that were not present in those two sources and produce(d) only one or two research publications.

stitutions, government-owned non-profit companies. Also included are private non-profit R&D organisations mainly serving the business enterprise sector, or privately funded research institutes and other R&D performing institutions.[11]

Data cleaning, unification, and consolidation of those papers to parent companies, was done using information on websites and occasionally Dunn & Bradstreet's Who Owns Whom Directory of corporate affiliations. The data were consolidated in mid-2002, in most cases at the "main organisational" level of the legal entity (i.e. parent companies, R&D labs, universities, research institutes, etc.). Corporate research laboratories, majority-owned subsidiaries and other corporate affiliations are included as much as possible in the immediate parent company, the ultimate domestic parent company, or company group. Jointly owned laboratories are assigned equally to the parent companies. Major mergers, acquisitions and divestitures are taken into account as much as possible. Companies added to the parent through mergers and acquisitions in the years 1996–2002 were renamed to the current parent company to ensure compatibility over time. Foreign branches and foreign subsidiaries of multinational companies are labelled with the consolidated name of the domestic ultimate parent. Each (parent) company is linked to the country of location mentioned in the author address.

Counts of co-authored papers are defined at the level of these main organisations.[12] Each organisation is defined at the highest aggregate level—the main organisational level. They are assigned to the country of location as listed in the affiliate address on the research publications. Dividing up a paper between the participating units (researchers, organisations, countries) is to some extent arbitrary—there is no fair method to determine how much money, effort, equipment and expertise each entity contributes the underlying research effort and writing the paper. Our basic assumption therefore is that each author, and associated organisation, made a non-negligible contribution. Consequently, we adopt a counting scheme in which each paper is fully allocated to each of the main organisations listed in the author address heading.

It is important to stress that an unknown fraction of the corporate research papers are probably not exclusively basic research-oriented; they will also relate to application-oriented ("strategic") research as well, and perhaps to a certain degree also "applied" research that is directly related to technological development. Since universities are generally accepted to be the major locus of curiosity-driven "blue sky" basic scientific research, corporate papers listing at least one university are assumed to more basic research-oriented as compared to co-publications listing non-university public sector research organisations. The papers jointly authored with non-university research organisations, and especially those with other firms, are assumed to represent strategic research rather than basic research.

The publication output analyses distinguish six types of industrial research papers: in addition to papers that were authored solely by one private sector organisation, we define the following mutually exhaustive categories of jointly authored research papers:

- two firms exclusively;
- three of more firms exclusively;
- one company with public sector organisations—including one or more universities;
- one company with public sector organisations—excluding universities;
- two or more firms with public sector organisations—including one or more universities;
- Two or more firms with public sector organisations—excluding universities.

3.3. Industrial sectors

Sector-level analyses will deal with two R&D-intensive high-technology industrial sectors: (1) biopharmaceuticals; and (2) the semiconductors industry. Both are characterised by strong relationships between research, technological development and innovation. Both involve difficult learning environments where

[11] In contrast to the OECD's *Frascati Manual* definition of the business enterprise sector, the current version of the CWTS delineation excludes non-profit institutions that are market producers of goods or services, specifically in the medical care sector (e.g. hospitals, clinics and medical practitioners in private practices), as well as other non-profit institutions serving business (e.g. trade associations and chambers of commerce).

[12] For example, a industry/university research paper written by five researchers: two from different Pfizer labs, one from a Pharmacia lab, and two from different research groups at Cambridge University, it will increment the count once for Pfizer, once for Pharmacia, and once for Cambridge.

research-based scientific and technical knowledge play an important role in knowledge creation and exploitation. Basic research in the bio-pharmaceuticals industry explores the genetic and bio-molecular mechanisms of diseases in relation to designs of drugs. For semiconductors, basic research includes the physics of solid-state devices and the chemistry involved in manufacturing integrated circuits. Corporate in-house longer-term research plays a stronger role in the bio-pharmaceuticals industry, where a firm's progress and competitive position is closely tied to advances in basic research and knowledge appropriation through patenting. The expected benefits of basic research for design of drugs are therefore much higher, than for example the design of new materials of semiconductors.

These sectors are defined in terms of a representative set of firms that were selected from two public databases previously or currently available on the Internet:

- "R&D Scoreboard 2001" compiled by the British Department of Trade which covers the annual accounts of the 500 largest R&D-spenders world-wide in the period 1996/97–2000/2001 (http://www.innovation.gov.uk/projects/rd_scoreboard/database/);
- "TR Patent Scorecard 2002", a joint effort Technology Review and CHI Research Inc., covering firm-level R&D-performance data based on CHI's analyses of their USPTO patents granted in 1996–2001.(http://www.technologyreview.com/scorecards/patent_2002.asp).

A join of both databases for the two industrial sectors resulted in the following sets of companies, which includes most of the large and scientifically leading firms across the globe:

- Bio-pharmaceuticals: 87 firms (55 North America, 16 Asia, 16 Europe).
- Semiconductors: 75 firms (51 North America, 21 Asia, 3 Europe).

The two lists of companies, and their countries of headquarters, are presented in Appendices A.1 and A.2. Each set includes those selected firms that published at least one research paper in 1996–2001 indexed within the ISI/CWTS database. Note that both sets are assumed to be representative only for the large research-performing companies in these sectors, and not necessarily so for the sector as a whole, which includes many high-tech start-ups, SMEs, or diversified companies that are also classified in another primary business sector. Nonetheless, given the number of selected companies and the fact that the selection includes the main R&D actors in these industries as well as being the main contributors of research papers in international journals, we expect a reasonable coverage of published basic research outputs by the entire industrial sector.

4. Results of the analyses

4.1. Diverging R&D output trends

To what extent are recent shifts in the marketisation of industrial R&D, as described in Section 2, visible in the corporate R&D literature? If the major business enterprises in the advanced industrialised countries have indeed spent the same amounts on in basic research in the 1990s, but have become more focused on strategic/applied research rather than basic research, and now promote the protection and exploitation of science-based knowledge rather than dissemination in the open literature, we should expect to find at least some of the following trends in the available empirical data: (1) more corporate researchers; (2) declining budgets for basic research; (3) more patents—especially science-based patents; (4) less research papers in the international scientific literature; (5) less research co-operation with other companies; and (6) more co-operative linkages with universities and other public sector research organisations.

Analysis of the CWTS database shows the following outcomes. World-wide some 290,000 corporate research articles were published in 1996–2001, which amounts to 6.5% of the world-wide publication output. The total publication output by the corporate sector shows a 12% decrease during the interval 1996–2001 and this annual decline is accelerating in recent years (4% in 2000; 10% in 2001).[13] Meanwhile, the share of public/private co-authored articles has risen from 57 to 68%. As for research inputs, according to OECD

[13] Resulting in a significant decline of industry's share in the world-wide scientific literature, from 7.0% in 1996 down to 5.6% in 2001.

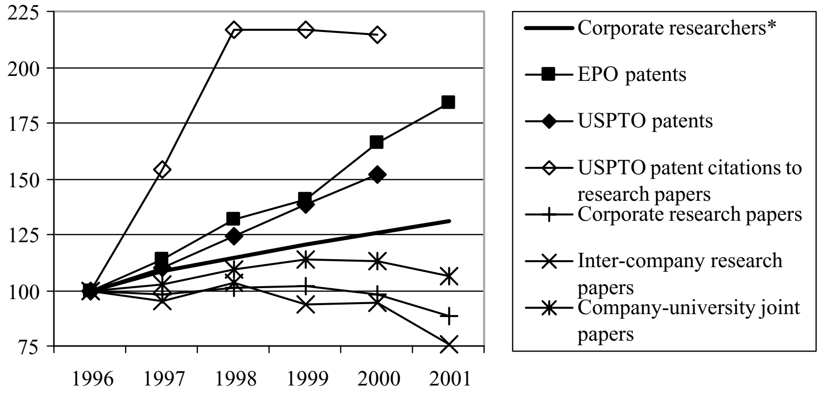

Fig. 1. Diverging R&D output trends—world-wide (1996 = 100). (*) We assume a 2-year time lag between trends in volume of researchers and R&D outputs published in the open literature. The numbers of researchers in the business sector within the OECD refer to the period 1994–1999 but are superimposed on the 1996–2001 time-axis for ease of comparison. Data sources: USPTO US Patent Statistics Report—Summary Table; US Science and Engineering Indicators 2002; EPO Annual Reports 2000 and 2001; ISI/CWTS database; OECD, MSTI database November 2001.

figures its member states spent on average about 0.4% of their GDP on basic research in the mid and late 1990s (OECD, 2001). However, country-level data on the share of the business sector is lacking, or difficult to compare, often due to shortcomings in the somewhat ambiguous concept “basic research” as defined in OECD’s Frascati Manual (Geullec, 2001).[14] More detailed information exists for only a few countries, including the US where the business sector itself collects data (Larson, 2000).[15] Fortunately, the OESO provides more comprehensive data on the quantity of researchers in the business sector. Using the trends on the total number of researchers in the OECD member states in the years 1994–1999 as a baseline, we can examine various R&D output trends in 1996–2000/2001. The results are presented in Fig. 1.

The longitudinal analysis shows steadily increasing numbers of industrial researchers (an unknown fraction of which being involved in basic scientific and engineering research) in conjunction with a divergence in the output trends between the two major classes of codified R&D information: large growth rates of patents versus a gradual decline of research papers in the journal literature. Moreover, we observe a significant growth rate in patent citations to the scientific literature, which underlines the observed emphasis on commercialisation of science-based industrial R&D.[16] The divergence between both types of R&D-output is of fairly recent date: the decline of corporate publishing has been a very gradual process up until 2000. Given the rate of divergence and average time lag between research inputs and published outputs, this bifurcation process must have started in the mid-1990s, which seems to coincide with anecdotal evidence from other sources (see Section 2.1). The results also exhibit a deterioration of inter-company co-publications which has dropped by 25% since 1996, while the numbers of industry/university co-authored articles has gradual fallen back to the 1996 level. So, it would appear that one of the main factors driving the declining publication

[14] OECD background papers contain provisional data pointing towards decreases in the US and Japan for corporate expenditure for basic research (OECD, 2001).

[15] Corporate R&D expenditure by US-based companies has increased by some 10% each year in the second half of the 1990s. Data collected by the US National Science Foundation show that basic research accounted for 9% of the total corporate R&D spending in 2000, shorter-term (“applied”) research at 20%, and the remainder of 71% for technical development (NSB, 2002). From 1995 to 2000, aggregate R&D expenditure increased by 63%, but basic research rose by 142% (Larson, 2001). The exceptionally strong growth rate is claimed to be a reflection of increased funds for corporate profits and available cash for future investments and risk taking, decreasing product cycle times and strong competition in increasingly global markets.

[16] The exponential growth of patent citations to research papers in international scientific and technical journals in the years 1996–1998 is in part due to changes in the US patent law in 1995 (NSB, 2002, pp. 5–53).

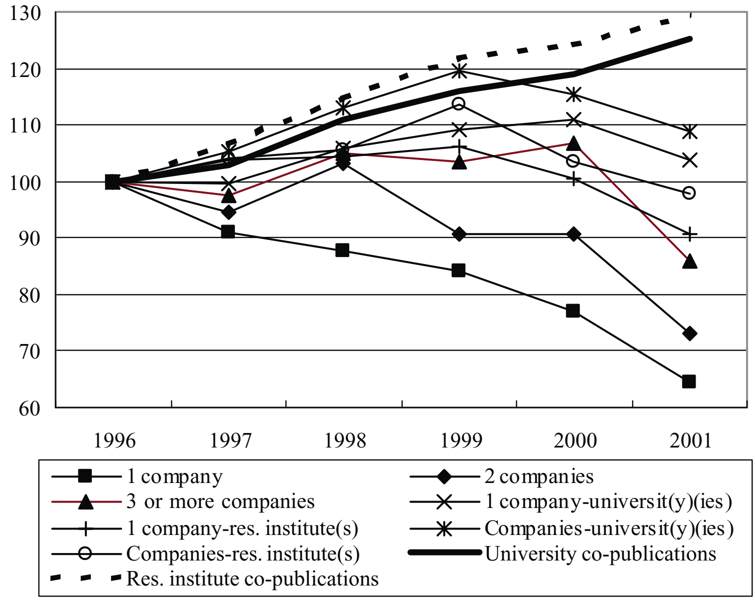

Fig. 2. Trends in corporate research publication output world-wide, and world-wide trends in institutionally co-authored research publications (1996 = 100). Data source: ISI/CWTS database.

output relates to whether or not research partners are involved in corporate basic research, and the type of partners involved.

Fig. 2 exhibits a further breakdown of the trend data by the various categories of co-authored research papers, as well as temporal changes in the numbers of single-company authored articles. The largest slide occurs for research papers listing only one company. We find an accelerating rate of decline in which the share of these papers has dropped significantly from 36 to 26% between 1996 and 2001. Co-publications involving pairs of companies are also in rapid decline. However, the drop in papers originating from research partnerships involving three or more firms is smaller than for pairs, suggesting different knowledge creation processes and appropriation regimes in corporate research partnering depending on the number of firms involved. It would seem that the larger the number of partners involved, the more the research will be of a generic “pre-competitive” nature and results are likely to be (partially) transferred into the open literature for strategic reasons.[17]

The general decline in the number of co-publications listing at least one company is in contrast with the co-publication trends in the university sector, and a second institutional sector covering the public sector research institutes and government laboratories.[18] Both public research sectors show a steady increase in co-publication activity, where the growth rate of the research institutes surpasses that of the universities. However, despite the larger growth rate, the co-publication output between companies and research institutes is decreasing at a faster pace than the corporate-university co-publication activity. Hence,

[17] Although these corporate co-publications do not list authors from the public sector, the research efforts reported in these papers may well include significant contributions from universities or research institutes. These contributions may become explicit in the acknowledgements or are added more implicitly in the list of references to relevant prior research articles by the academic partners.

[18] The overall data for the co-publication outputs in the three institutional sectors (universities, public sector research institutes, and companies) contain double counts owing to the nature and definition of these joint publications. For instance, university co-publications are defined institutional co-publications at the main organisational level (i.e. excluding collaboration within organisations) that include at least one author address referring to a university. Hence, these university co-publications overlap with the co-publications for the public sector research institutes and/or corporate sector in those cases where organisations from those other sectors are listed in the author address(es).

corporate co-authoring seems to be focusing more and more on the university sector, hinting a gradual shift towards more joint 'basic' research with academics and less joint 'application-oriented' research in collaboration involving non-academic scientists and engineers at the public research labs.

When universities are engaged in research partnerships with industry they act mainly as producers of basic knowledge and advanced technical skills (and associated human capital in the form of Ph.D. students and researchers), while industrial research partners focus on the transfer, absorption and assimilation of that knowledge and know-how. This relatively clear-cut division of labour and responsibilities, in conjunction with industry's never-ending need for new inputs of leading-edge scientific knowledge, instruments and skills, ensures a fairly stable quantity of joint research papers with academics. The quantity of industry-university co-authored publications showed a 13% gain during 1996–2000, which then slipped back to 6% in 2001. Due to the larger rates of decline of the other categories of corporate papers, the fraction of these articles in the corporate output has increased steadily from 48% in 1996 to 58% in 2001. Coupling industry's increased need for research co-operation with universities, and the output-rewarding incentive systems in the academic community, would seem to ensure a sustained flow of industry/university research papers reflecting knowledge flows from academia to their partner firms for their in-house research, technological development and further commercial use, as well as contributing knowledge to the world-wide research community.

Interestingly, industry/university co-publications involving multiple firms are less affected by the general downturn compared to single company co-publications with universities. As the size and heterogeneity of public/private research alliances and networks grows, especially those aimed at producing scientific or technical knowledge to be shared amongst all (major) partners, the more prone these partnerships seem to be to disseminate research information into the public domain—most likely also to satisfy the participating academics who need to comply to publication output-driven rewards systems (e.g. Tijssen, 1998). In contrast, the volume of joint papers involving research institutes, or other non-academic partners in the public sector, do show a noticeable decline since 1996. Since non-university public sector researchers are less active in basic research and less driven by publishing papers in the international journal literature, their numbers of joint papers with industrial researchers are now also decreasing significantly. Overall, we see a pattern, similar to the trend found in the inter-company partnerships, where the number of partners involved in public/private co-publications is inversely correlated with the rate of decline.

4.2. Research output trends by industrial sector

Obviously, the overall trends depicted in Figs. 1 and 2 hide a large degree of variation. It stands to reason that the underlying (changes in) volume of basic research and/or decreasing publication activity will vary by industry. A recent bibliometric study by Lim (2001), using research articles in international journals and USPTO patents, indicates a strong link between both outputs in the bio-pharmaceuticals sector but a weaker relationship in the semiconductors industry. Lim argues that these differences are due to sector-level differences in the relevance of basic research for innovations in conjunction with firm-level differences in absorptive capacity of knowledge spillovers.

Fig. 3 exhibits the breakdown of the various types of corporate research papers for both sectors, disclosing some sector-specific characteristics and developments (the underlying data are presented in Appendix B.2). The large bio-pharmaceuticals companies produced a staggering 55,962 papers in 1996–2001, displaying a remarkably high propensity to produce multiple-company papers that remained fairly stable in the years 1996–2001. This would seem to indicate a sustained tendency on the part of these (large) firms to take part in inter-company or intra-company research alliances.[19]

The large semiconductors companies, producing a total of 15,641 papers, exhibit a very large growth of papers from partnerships involving one company and one non-university public research organisation. Although the number of these papers is fairly small (51 in 2001), the volume has risen by some 30% since 1996 and remained stable. Furthermore, the quantity

[19] The set of inter-company co-publications includes co-authored papers listing different national affiliates or subsidiaries of the same (ultimate) parent company located in different countries.

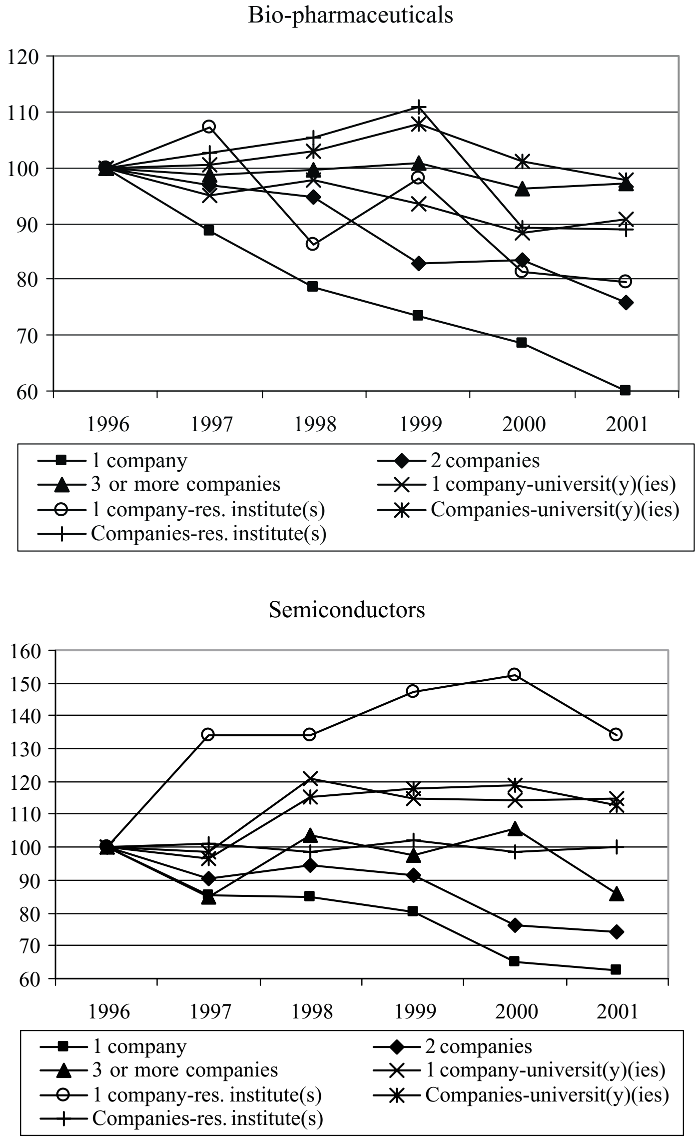

Fig. 3. Trends in corporate research publications world-wide by field (1996 = 100). Sources for company selection: “TR Patent Scorecard 2002” (Technology Review and CHI Research Inc.); “R&D Scoreboard 2001” (British Department of Trade). Data source: ISI/CWTS database.

of papers listing several companies and one or more research institutes remains stable. This sector-specific finding ties in with the results of Lim (2001) suggesting that semiconductor firms depend primarily on applied knowledge rather than basic knowledge. In the semiconductors industry, many intermediate steps are required to transform basic scientific breakthroughs into useful innovations, which reduces their need to invest heavily in their own longer-term research. R&D-based semiconductors firms seem to have increased their investments in pre-competitive research at research institutes in the public sector, rather than boosting in-house basic or strategic research, or engage in strategic research ventures with other firms. The technology-oriented research institutes in the public sector, rather than general universities or technical universities, are sought out by the semiconductors industry as the main sources of applied scientific knowledge.

Similarly to the overall picture presented in Fig. 2, these two graphs are likely to hide marked differences between the large firms, especially between science-based first-moving "innovators" and the "followers" that spend less of their resources on R&D and basic research in particular. However, given the lack of this kind of firm-level data, we can only assume—for now—that in view of the increasing international competitive pressures in both sectors, and the business practices shared by the major firms, there is no compelling reason to believe that large companies active in the same fields and competing in the same local or global markets, are adopting fundamentally different strategies for enhancing the commercial pay-offs of their research efforts.

4.3. Breakdown of research output trends by triad region

Corporate research activities follow to a certain degree "universal" scientific methods, rules of conduct and research output dissemination strategies, but also adhere to common business practices and economic rationales (e.g. optimising cost-effectiveness of research efforts and enforcing IPR regimes). This being the case, to what extent do different industrial research cultures, national R&D environments and innovation systems that exist across the globe impact on the magnitude and trends in publication output of industrial researchers in peer-reviewed international scientific and technical journals? This geographical dimension of industrial research has attracted a great deal of policy interest in recent year, especially with respect to the effectiveness of public policies and mechanisms to support public–private research co-operation (OECD, 2002). The publication output of corporate researchers at firms active within the same industry, but located in different countries or continents, may shed some empirical light on these geographical differences, especially with respect to joint research ventures between firms and public–private research co-operation.

Fig. 4 displays the general output trends per industrial sector broken down by the "triad" regions in which the company is located, i.e. Europe, North America (predominantly US), and Asia (predominantly Japan). The underlying data are presented in Appendix B.2.[20] The results in Fig. 4 display at least one striking difference in the case of the Bio-pharmaceuticals sector, where Asia exhibits a noticeable growth of joint publications involving companies and public research institutes, as opposed to the marked decline in North America. On the whole, public–private co-publication frequencies remain fairly stable in Asia, whereas both Europe and North America display a gradual drop in output. Given the relatively small quantities of publications in some cases it is too early to draw any definitive, and statistically sound, conclusions. Nevertheless, it seems fair to assert that Asian firms are acting different than their counterparts in the Western world with respect to their partnering in the public sector. Apart from the remarkable rise of European research publications in 1999 and 2000 listing three of more companies (which may well have resulted from an insignificant annual fluctuation), each triad region shows the same significant downward trend in corporate publication output that originates from firms exclusively.

In the semiconductors industry, we observe the same differences in trends between Asia and the US.[21] Public–private co-publication activity is clearly on the rise in Asia, especially co-operation involving non-university research institutes. In contrast, the research output of US companies is characterised by declining quantities of public–private research papers, most notably those involving non-university research institutes. In both cases, the rates of changes are significant.

The increasing importance of collective research mechanisms, both among companies and well as among academia and companies, is now generally acknowledged to be one of the fundamental global changes taking place in the way (science-based)

[20] Due to the small quantities of publications, resulting in large annual output fluctuations, the two categories of public–private co-publications involving non-university research institutes are collapsed into one joint category.

[21] Europe is left out of this analysis given the small number of semiconductor firms based in European countries.

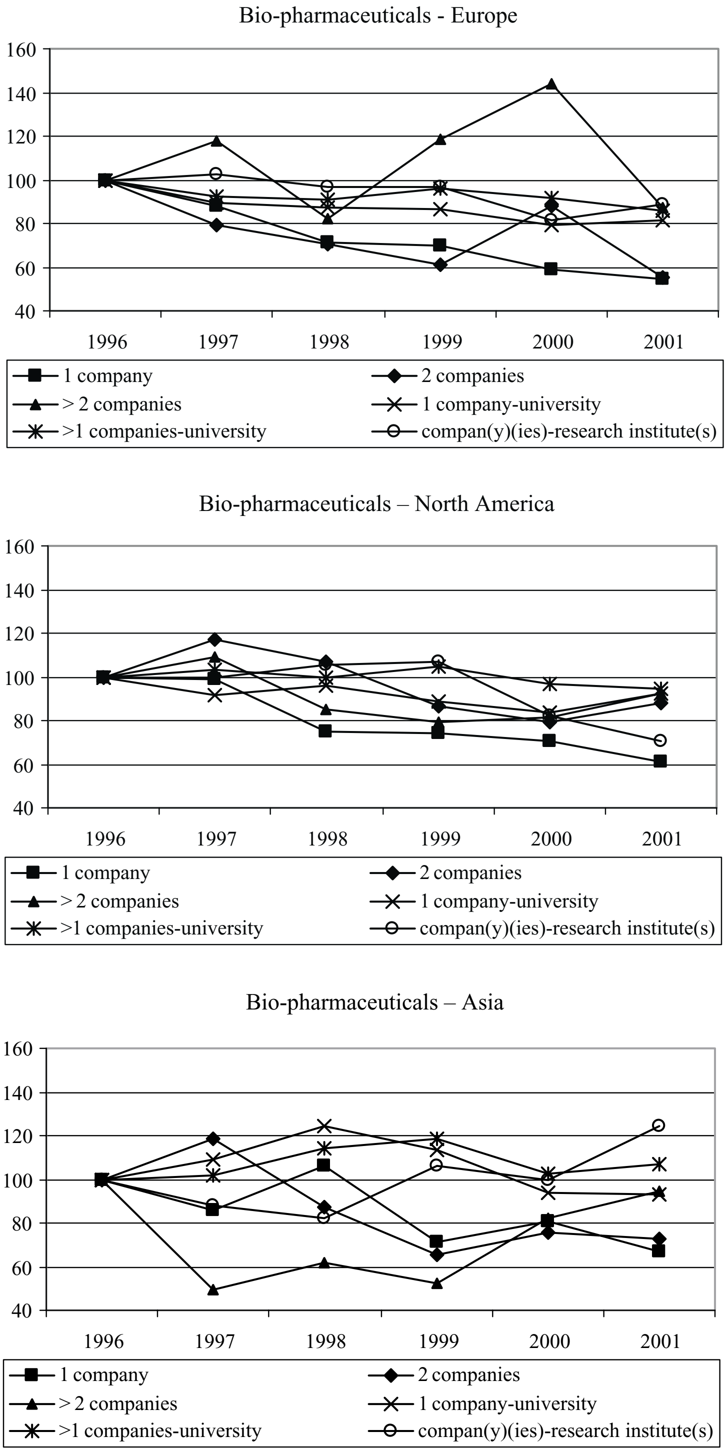

Fig. 4. Trends in corporate research publication output by field and triad region (1996 = 100). Data source: ISI/CWTS database.

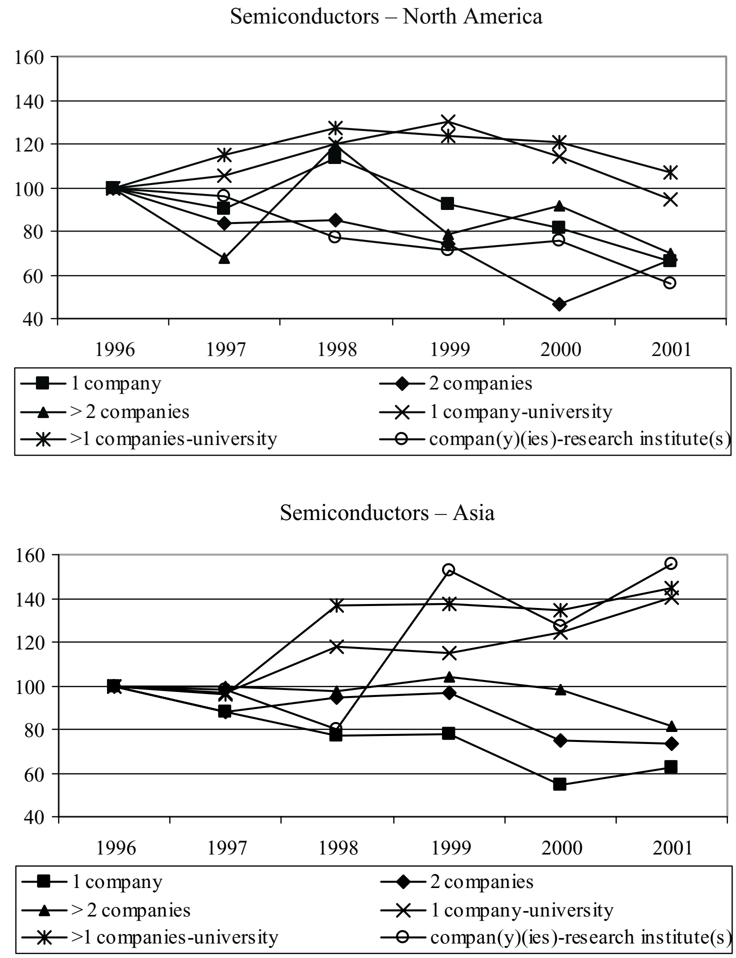

Fig. 4. (*Continued*).

technological innovation is brought about (Gibbons et al., 1994; OECD, 2002). Judging by these empirical data in these two science-based industries, the direction or pace of this evolution differs across the globe: the American and European companies appear to be downsizing the basic research efforts or at least restricting the dissemination of results in international journals, whereas their Asian competitors seem to focus more strongly on basic research activities and/or publish more research articles in peer-reviewed international journals. The diverging Asian trend predominantly reflects an increased focus on basic research within Japanese companies. Recent bibliometric research by Hayashi (2003) in fact provides case-study empirical confirmation that this rise in output results in part from government programmes that promote university-industry research collaboration. His findings show that several Japanese R&D programmes, such as the Next Generation Programme, have been instrumental in increasing the number of public–private co-publications in international journals.

As outlined in previous sections, the changing patterns of collaboration may not only reflect such "external" country/region-specific pressures on corporate research, but also "internal" company/industry-specific factors. Clearly, further case-study research is needed to help explain these converging trends between the US/Europe and Asia, as well as the degree of similarity in trends between US and Europe, and attempt to disentangle the role of internal and external factors that are driving public–private research collaboration and corporate R&D networking within the Triad regions. The pivotal policy question that remains: do the declining numbers of research papers of the US and European companies indeed indicate that corporate research is in decline in the Western world? Or, alternatively, that the commercialisation of corporate research is further advanced? The final section will deal with this issue in more detail.

5. Discussion and concluding remarks

Clearly, a 6 years time-span is not enough to detect structural global changes and trends with any degree of certainly. However, the results of this large-scale study would at very least suggest that the erosion of industry's contribution to the open scientific and technical literature has gained momentum at the turn of the millennium. We might be tempted to conclude that this recent development follows from companies switching their priorities to short-term research focused on areas close to the market where they can make money more quickly. These competitive pressures to increase private rates of return, and to boost commercialisation of research findings, may well have redirected the goals of basic research and narrowed the focus towards strategic and applied research with shorter time-horizons. Indeed, companies are most likely also trying to minimise research costs by contracting out for work rather than conducting in-house research. Less funding for in-house exploratory research, and the downsizing of industrial research labs, would account for the significant decrease of corporate research articles in the open literature, especially the dramatic decline in publication rates of papers where companies are the sole creator of new scientific knowledge, as well as the significant drops in inter-company co-publications. Moreover, the relatively minor effect on industry-university papers can be explained by closer links with the university sector.

The downturn in corporate spending on in-house basic research would also account for the significant differences we observe between output trends in joint papers with two partners and those listing three or more partners. Assuming that the co-publications listing many partners arise from joint ventures and consortia that are primarily engaged in pre-competitive research of a more generic nature, these partnerships have less reason to appropriate collective knowledge and impose restrictive publishing strategies. In other words, in the case of basic research involving many partners, either in the corporate sector or public sector, knowledge dissemination practices tend to be less vulnerable to changes in corporate research culture. As for the industry's links with non-academic research organisations in the public sector, it is fair to assume that these partnerships are more focused on strategic or applied research and therefore more affected by withdrawals from open science. Moreover, publishing findings from this kind of joint research is likely to be more severely constrained by IPR arrangements and publication strategies, as compared to industry/university co-authored papers, in the light of the (perceived) commercial value of such research findings and the greater risk of unintended spillovers.

However, other organisational and socio-economic factors might also (partially) explain these changes within corporate research culture and its effect on the propensity to publish in peer-reviewed journals. As state-of-the-art research has become more complex and expensive, and driven by tighter time schedules, research projects have become subject to stricter "costs and returns" accounting rules that focus on milestones, tangible deliverables and value creation. As a result, the production of research articles has gone down because producing investing time and efforts in writing these papers has become increasingly prohibitive, while other performance targets and R&D results such as patents and patent-based licenses are more highly rewarded and generate greater in-house recognition and reputation. Alternatively, or additionally, researchers may have gradually opted for other "easier" publication outlets with less severe refereeing such as internal report series, contributions in conference proceedings, or papers in professional journals.[22]

[22] Industry's influence on the scientific progress in the global research system, and its contribution to the open scientific publication system, may therefore in part be hidden from public scrutiny. Moreover, a firm's research partners at universities and public sector research institutes might still publishing results of joint efforts in international journals without mentioning the (monetary)

Only the truly high-quality papers are still submitted to peer-reviewed international journals, where related research papers of lesser scientific significance, or earlier abridged versions of the same paper, are made public through other outlets.

Concluding, the whole pattern of observations point in the direction of structural changes in corporate priorities and strategies concerning basic research leading to codified knowledge that is—in principle—publishable in the open scientific and technical literature. The observed trends in the output of corporate research articles published in recent years suggest that on the one hand that corporate basic research is being downsized, but on the other hand we can see that corporate priorities concerning access to their research-based knowledge, and securing related intellectual property rights, are probably also getting the better of sharing and exchanging information with the world-wide scientific community.

The correlation and causality between diminishing resources for corporate basic research and the declining output levels requires further investigation. Based on the findings presented in this paper we cannot rule out the possibility that science-based companies might well still be doing the same magnitude of long-term research (or maybe even more that before), but their R&D labs and research managers now operate in different organisational and managerial structures that are governed by rules and regulations aimed at maximising the efficiency of knowledge creation processes and broadening the opportunities for commercial gains of research activities. This assumption is backed up by general observations of US industry (Larson, 2000), as well as in-depth firm-level analyses by Buderi (2000a) that indicate "… the extended time horizon of central labs is why many [industrial R&D] directors insist that basic research is alive and well—if not thriving".[23] Coupled with IPR-driven knowledge appropriation regimes and more restrictive policies for dissemination of findings of general scientific importance makes researchers shy away from publishing in peer-reviewed scientific and technical journals.

In the event that this is actually the case, a significant fraction of the research is probably never published in the open literature, which may negatively affect the progress of science.[24] Moreover, one cannot rule out the possibility that the academic partners might still be publishing results of joint efforts but refrain from mentioning the direct involvement of industrial researchers or adding references to the sources of private funding. If this is becoming the case, the growing part of industry's research efforts, its impact on academic research, and the commercialisation of research results, will be hidden from public scrutiny. Already there is a strong feeling within the scientific community that industry's trend towards 'closed science', and closer ties to universities, endangers the public accountability and intellectual independence of public sector basic research (Nature, 2001). For this reason, several major scientific journals, like *Nature* and *Science*, have implemented editorial policies forcing authors to explicitly acknowledge such ties with industry, and business interests of researchers, in statements attached to their journal articles.[25]

The key question we face at this point in time is whether or not these recent changes in industry's research publication output indicate structural and lasting transformations that are reshaping the world-wide corporate science landscape? Or do these trends signal

resources supplied by the corporate sector. For this reason, several high-profile scientific journals, like *Nature*, have implemented editorial policies forcing authors to explicitly acknowledge such ties with industry.

[23] The situation caused the economic downturn after the turn of the millennium is unclear: on the one hand, we might expect the growth in this type of research to continue as we move further into a new knowledge-driven economy. On the other hand, although managers of the larger high-tech firms will try to protect research budgets to secure longer term survival and growth, corporate expenditures of risky long-term research will probably be amongst the first to be scrutinized and possibly sacrificed, predicting tough times ahead for many corporate research laboratories and their partners.

[24] This trend endangers the way open science has worked, with substantial success, for centuries where scientific discoveries have been traditionally put into the public domain. If they are now patented or not published, access to scientific knowledge will be restricted, or at least will be more costly. This is especially detrimental to science when research tools and databases are concerned. As an increased number of discoveries are protected, researchers have to spend more time negotiating access, and spend more resources for paying fees and royalties. The solution is to put in place legal provisions that allow the use of protected knowledge "for purpose of research".

[25] So, far about 4% of papers published in *Nature* in the last two years have the authors declared competing interests (Nature, 2003). This share is only slightly less than industry's 6.5% contribution to the worldwide scientific literature (see Section 4.1).

temporary adjustments of business priorities amongst the science-based large firms to cope with cyclic developments affecting the competitive global markets in which they operate? The findings of this exploratory study are obviously suggestive rather than conclusive, and further case studies are necessary to corroborate the tentative conclusions with more detailed information at the company level and industry level. Nonetheless, these first empirical findings do raise a number of important unanswered questions, and related criticism voiced by the scientific community regarding the negative impact on public research organisations in terms of influencing basic research agenda's, sharing of information and materials, and enforcing secrecy (e.g. Nature, 2001).

More specifically, to what extent are the business strategies of firms, and cost projections their of in-house basic research, negatively affecting their reservoir of new scientific knowledge and technical know-how to explore new technological opportunities and generate advanced technologies? How is this process shaping the nature and direction of scientific progress in global science, and the co-evolution of public and corporate science, in terms of the free dissemination and exchange of knowledge? And have these changes affected industry's absorptive capacity of new knowledge? Given the wealth of data contained in the large quantity of papers published by corporate researchers, further empirical research would certainly benefit from in-depth analyses of industry's contribution to the international scientific and technical journals.

Acknowledgements

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Appendix A

A.1. Selected (parent) companies and country of headquarters—pharmaceuticals

Abbott Laboratories	USA	Immunomedics	USA
Affymetrix	USA	Incyte Genomics	USA
Alliance Pharmaceutical	USA	Invitrogen	USA
Amgen	USA	Isis Pharmaceuticals	USA
AstraZeneca	UK	Kowa	Japan
Augustine Medical	USA	Kyowa Hakko Kogyo	Japan
Aventis	USA	Ligand Pharmaceuticals	USA
Biogen	USA	Lynx Therapeutics	USA
BioMerieux	France	Merck & Company	USA
Bionumerik Pharmaceuticals	USA	Millennium Pharmaceuticals	USA
Biovail	Canada	Neorx	USA
Boehringer-Ingelheim	Germany	Neurogen	USA
Boots	UK	New England Biolabs	USA
Bristol-Myers Squibb	USA	Novartis	Switzerland
British Biotech	UK	Novo Nordisk	Denmark
Caliper Technologies	USA	NPS Pharmaceuticals	USA
Celgene	USA	Ono Pharmaceutical	Japan
Cell Therapeutics	USA	Pfizer	USA
Celltech Chiroscience Group	UK	Pharmacia	USA
Cephalon	USA	Pharmacopeia	USA
Chiron	USA	Promega	USA
Chugai Pharmaceutical	Japan	Ribozyme Pharmaceuticals	USA
COR Therapeutics	USA	Roche	Switzerland

Appendix A (*Continued*)

Corixa	USA	Sanofi-Synthelabo	France
Corvas International	USA	Schering	Germany
Curis	USA	Schering-Plough	USA
Daiichi Seiyaku	Japan	Seikagaku	Japan
Eisai	Japan	Senju Pharmaceutical	Japan
Elan	Ireland	Sepracor	USA
Eli Lilly	USA	Shionogi & Company	Japan
Emisphere Technologies	USA	Shiseido	Japan
Enzon	USA	Sigma-Tau Industrie	Italy
Fresenius Chem-Pharm	Germany	Synaptic Pharmaceutical	USA
Fujisawa Pharmaceutical	Japan	Taisho Pharmaceutical	Japan
Genentech	USA	Takeda Chemical	Japan
Genzyme	USA	Tanabe Seiyaku	Japan
Gilead Sciences	USA	Tularik	USA
GlaxoSmithKline	UK	Vertex Pharmaceuticals	USA
Guilford Pharmaceuticals	USA	Wyeth	USA
Heska	USA	Xoma	USA
Hisamitsu Pharmaceutical	Japan	Yamanouchi Pharmaceutical	Japan
Human Genome Sciences	USA	Zambon Group	Italy
Hybridon	USA		
ICOS	USA		
IGEN International	USA		
Immunex	USA		

Sources: DTI's UK R&D Scoreboard 2002; Technology Review/CHI Research's TR Patent Scorecard 2002.

A.2. Selected (parent) companies and country of headquarters—semiconductors

3Com	USA
Acer	Taiwan
Adaptec	USA
Altera	USA
Analog Devices	USA
Apple Computer	USA
ATI Technologies	Canada
Casio Computer	Japan
Cirrus Logic	USA
Compaq Computer	USA
Conexant Systems	USA
Dell Computer	USA
EMC	USA
Fujitsu	Japan
Harris	USA
Hewlett-Packard	USA
Hitachi	Japan
Imation	USA
Integrated Device Technology	USA
Intel	USA
Intersil	USA
Kla-Tencor	USA
Kyocera	Japan
Lam Research	USA
Lattice Semiconductor	USA
Lexmark	USA

Appendix A (*Continued*)

Linear Technology	USA
LSI Logic	USA
Marconi	UK
Microchip Technology	USA
Micron Technology	USA
Mitsubishi Electric	Japan
Motorola	USA
Murata Manufacturing	Japan
NEC	Japan
Novellus Systems	USA
Oce	Netherlands
Omron	Japan
Read-Rite	USA
Rohm	Japan
Silicon Graphics	USA
STMicroelectronics	France
Storage Technology	USA
Sun Microsystems	USA
Taiwan Semiconductor	Taiwan
Teradyne	USA
Texas Instruments	USA
Tokyo Electron	Japan
Toshiba	Japan
United Microelectronics	Taiwan
Western Digital	USA
Xerox	USA
Xilinx	USA

Sources: DTI's UK R&D Scoreboard 2002; Technology Review/CHI Research's TR Patent Scorecard 2000.

Appendix B

B.1. Trends in publication output frequencies (see Fig. 1)

Organisational origin of research publication[a]	1996	1997	1998	1999	2000	2001
(a) 1 company exclusively	17454	15894	15308	14704	13425	11253
(b) 2 companies exclusively	2626	2484	2708	2385	2383	1916
(c) >2 companies exclusively	724	707	761	750	772	621
(d) 1 company and at least 1 university[b]	12275	12243	13011	13389	13608	12749
(e) >1 companies and at least 1 university[b]	11334	11936	12800	13563	13077	12340
(f) 1 company and at least 1 research institute[b]	2053	2132	2140	2177	2063	1859
(g) >1 companies and at least 1 research institute[b]	2320	2415	2451	2635	2400	2269
(h) University co-publications[c]	275106	283060	305129	319125	327200	344777
(i) Research institute co-publications[d]	68746	73404	78958	83805	85428	89023

[a] Main organisation(s) listed in author affiliate address(es).

[b] Each research paper is attributed in full to all (main) organisations, and their institutional sector, listed in author addresses. Hence, papers belonging to categories (d) to (g) may also list a non-targeted institutional sectors (research institutes in case of category (d) and (e), and universities in case of (f) and (g). The frequency data are de-duplicated at the level of institutional sectors, but will include multiple counts for cases with different sectors.

[c] Publications listing at least one university and one other main organisation (university or non-university).

[d] Publications listing at least one (non-university) research institute and one other main organisation.

B.2. Trends in publication output frequencies (see Figs. 2–4)

Industry sector—country/region; organisational origin of research publication[a]	1996	1997	1998	1999	2000	2001
Bio-pharmaceuticals—World						
1 company exclusively	3440	3050	2698	2526	2362	2068
2 companies exclusively	868	841	821	719	725	659
>2 companies exclusively	369	364	368	372	355	358
1 company and at least 1 university	2485	2359	2428	2321	2196	2255
>1 companies and at least 1 university	2464	2478	2538	2659	2489	2412
>1 companies and at least 1 research institute	323	346	278	317	263	257
>1 companies-research institute(s)	357	366	376	396	319	317
Bio-pharmaceuticals—Europe						
1 company exclusively	866	759	619	604	510	475
2 companies exclusively	417	330	294	255	367	231
>2 companies exclusively	251	296	207	298	361	219
1 company and at least 1 university	459	409	402	397	364	374
>1 companies-university	998	922	908	961	916	859
Compan(y)(ies)-research institute(s)	170	174	165	165	139	151
Bio-pharmaceuticals—North America						
1 company exclusively	1368	1355	1022	1012	964	840
2 companies exclusively	546	641	585	471	432	479
>2 companies exclusively	412	449	350	326	335	382
1 company and at least 1 university	562	517	540	497	472	521
>1 companies and at least 1 university	1128	1169	1120	1182	1095	1065
Compan(y)(ies)-research institute(s)	294	294	309	314	241	207
Bio-pharmaceuticals—Asia						
1 company exclusively	369	316	391	264	299	247
2 companies exclusively	192	227	168	125	145	140
>2 companies exclusively	130	64	80	68	107	123
1 company and at least 1 university	102	111	127	116	96	95
>1 companies and at least 1 university	235	240	269	278	241	251
Compan(y)(ies)-research institute(s)	33	29	27	35	33	41
Semiconductors—World						
1 company exclusively	1186	1013	1006	955	774	742
2 companies exclusively	300	272	284	275	229	222
>2 companies exclusively	86	73	89	84	91	74
1 company and at least 1 university	478	471	579	549	547	549
>1 companies and at least 1 university	586	565	676	691	697	661
1 company and at least 1 research institute	38	51	51	56	58	51
>1 companies and at least 1 research institute	84	85	83	86	83	84
Semiconductors—North America						
1 company exclusively	330	297	375	305	268	218
2 companies exclusively	132	110	112	98	61	88
>2 companies exclusively	46	31	55	36	42	32
1 company and at least 1 university	122	129	146	159	139	115
>1 companies and at least 1 university	316	363	402	390	381	337
Compan(y)(ies)-research institute(s)	70	67	54	50	53	39

Appendix B (*Continued*)

Semiconductors—Asia						
1 company exclusively	803	705	620	623	436	500
2 companies exclusively	405	355	383	393	304	298
>2 companies exclusively	184	183	179	192	180	150
1 company and at least 1 university	119	115	140	137	148	167
>1 companies and at least 1 university	268	257	366	369	361	387
Compan(y)(ies)-research institute(s)	59	58	47	90	75	92

[a] Main organisation(s) listed in author affiliate address(es).

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