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INDICATORS FOR SYSTEMS OF INNOVATION AND SYSTEM INTERACTIONS

Technological collaboration and inter-active learning

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ABSTRACT

The paper reviews the progress that has been made over the last ten years in the measurement and analysis of knowledge flows between the various institutions involved in "systems of innovation". It shows that this has involved both more imaginative use of existing data (such as patent statistics and data on scientific publications and citations) and the gathering of new datasets by means of firm-level surveys (CIS, PACE and Yale) and other techniques (MERIT-CATI databank on alliances). Very often the most interesting results have emerged from studies that have sought to combine some of these measures (for example patent citations and strategic alliances) to examine the nature, extent and effects of knowledge interactions.

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INTRODUCTION

This paper is concerned with measurement issues related to two major themes emerging from the recent innovation literature which have also become incorporated in policy debates: 'systems of innovation' and the 'knowledge-based' economy. The key element of the systems of innovation approach is that it treats explicitly the deliberate "intangible" investment in technological learning activities. Such learning or knowledge-creating activities involve a variety of institutions, principally business firms, universities, other education and training institutions, and governments. The underlying rationale is that successful knowledge creation, which is a necessary condition for improving welfare within a country, depends on the performance of these institutions as well as how well they interact as a system.

This approach is in contrast to the models of technical change and related policy prescriptions that were prevalent in the 1960s and early 1970s (Arrow (1962a and b) and Salter (1966)). Technical change comprised three elements:

➨ "embodied" technical change resulting from investment in better practice vintages of machinery;
➨ "disembodied" technical change resulting from the relatively costless diffusion of knowledge as codified "information";
➨ "disembodied" technical change with productivity increases resulting from "learning by doing" - a costless external benefit from production experience.

Much emphasis was put on the diffusion of technology which consisted of easily transmissible information (e.g. blueprints and operating instructions), improvements embodied in machinery, and the learning benefits of production experience.

However since then our knowledge of the nature and determinants of technological change has greatly improved as a result of case studies of firms and industries as well as a range of statistical analyses based on publicly available data on innovation indicators (Freeman (1994)). These studies show that both material artefacts and the knowledge to develop and operate them are complex, involving multiple dimensions and constraints in performance, that cannot be reduced to codified "information", whether in the form of operating instructions, or predictive models and theories. Tacit knowledge - underlying the ability to cope with complexity - is acquired essentially through experience, and trial and error (Kline, 1990). But it is misleading to assume that such trial and error is either random, or a purely costless by-product of other activities like "learning by doing". As technological activities over time have become increasingly complex, tacit and other forms of knowledge are increasingly acquired within firms through deliberate and often costly investment in what can be called "change-generating" activities, such as product design, production engineering, quality control, staff training, research, and/or the development and testing of prototypes and pilot plant (Bell and Pavitt, 1993).

Innovation studies have also shown that an essential element of contemporary knowledge generation[1] is its specialised nature:

- Specialisation by discipline within science and technology.
- Specialisation by corporate function inside the business firm, with the establishment of R & D laboratories. And - within the corporate R & D function - specialisation between the development function concerned with product and process development, and the research function exploring options for future product development.
- Specialisation by institution within countries, with R & D laboratories funded by companies, and by governments - either directly or through universities and similar organisations.

Specialisation implies co-ordination - and even integration - so that an essential feature of all effective "systems of innovation" are the linkages or interactions between their component parts: between disciplines, between corporate functions and between institutions. However, most of the previous empirical work based on 'systems of innovation' approach has concentrated on comparisons between different countries at a 'macro' level together with a description of the various institutions involved in national innovative activities (Lundvall (1992), and Nelson (1993)). Only a limited number of studies have gone beyond this to measure and analyse the quantitative importance of different institutions and the interactions or knowledge flows between them.

[1] The currently fashionable term is "knowledge production".

The aim of this paper is to examine the ways in which quantitative measures have been used to map three main types of knowledge flows:

- ➨ inter-sectoral transactions embodying flows of technological knowledge
- ➨ interactions among firms, primarily joint research activities and other technological collaborations
- ➨ interactions among firms and institutions engaged in basic research such as universities and public research institutes

Each of these is the subject of Sections 2 to 4, and in Section 5 we present some conclusions and areas for future research.

INTER-SECTORAL FLOWS OF TECHNOLOGY

The underlying rationale behind the studies concerned with inter-sectoral flows of technology is that one of the main channels of such flows are the new products produced by firms in a particular sector which enter as capital equipment or intermediate inputs into the production processes of other firms in other industries. Such flows are important in assessing the innovative performance of sectors: e.g. those sectors with low levels of 'own' R&D expenditures, such as services or construction, may nevertheless be recipients of significant amounts of 'indirect' R&D through purchase of new materials and equipment. They are also important in assessing the full impact of technology on productivity growth in a particular industry. Thus including measures of 'indirect' R&D significantly improves the results of econometric models attempting to explain industrial productivity growth by investment in R&D (Scherer (1984) and Ducharme (1991)).

There are 3 main measures which have been used to map inter-sectoral flows of technology in the literature:

- ➨ *Innovation counts* data based on survey information;
- ➨ Combined use of *Patent Statistics* and *R&D Expenditures* data;
- ➨ Combined use of *Input-Output Matrices and R&D Expenditures*;

The most direct way in which inter-sectoral flows of technology have been measured is by using survey information on more than 4000 major innovations commercialised in the UK, collected at the Science Policy Research Unit over the period 1970-84. The procedure was to write to experts in each sector of industry and commerce, asking them to identify significant technical innovations that had been commercialised in the UK since 1945, and to name the firm responsible. Questionnaires were sent to these innovating firms requesting information on a whole range of variables including the firm's and subsidiary's principal product line, and those of the innovation and its first user. On the basis of these data Robson et. al. (1988) have analysed the most important inter-sectoral technology flows in the UK economy.

The pioneering and unique work of Scherer (1982) uses US patent data linked to R&D expenditures for some 443 large US corporations to construct a matrix of inter-industry technology flows through the US economy. For each of more than 15,000 patents granted to these corporations, researchers manually assigned an industry of origin and upto 3 main industries of use using many different firm-level sources of information. Data on R&D expenditures by the 443 companies, disaggregated into unusually detailed product lines were available from the Federal Trades Commission (FTC) Line of Business Survey. Each patent was associated with an average share of inventing company's R&D expenditure in the particular product line and an equivalent benefit was flowed out to the user sector. The underlying rationale of this procedure is that patents are the main carriers of 'R&D' activities across industries. Ducharme (1991) and Hanel (1994) have used Canadian patent data for similar analysis where the main added advantage is that Canadian patent examiners, upto the 1980s, were routinely expected to allocate each patent to an industry of origin and an industry of use.

However both the approaches to measuring inter-sectoral flows of technology outlined thus far have one major practical drawback which is that they are very costly to implement and hence difficult to replicate. The final approach is easier to implement as it employs the combined use of input-output matrices and R&D expenditures (Terleckyj (1974) and Papaconstantinou (1998)) which are more readily available. The underlying rationale is that purchased inputs (both of capital equipment and of intermediate goods) act as carriers of technology across industrial sectors. Thus at any given point in time the products of a given industry embody its own R&D and part of the R&D of the upstream industries from which it has purchased various inputs. The assumption in such studies is that the amount of acquired

R&D is proportional to the quantity of goods purchased. Moreover the more sophisticated analyses such as Papaconstantinou (1998) track all the linkages further back in the production chain in calculating technology flows and also take into account technology acquired through foreign imports.

There are considerable similarities in the results from these studies and they can be summarized as follows:

➨ In most industrially advanced countries, more than 75% of the production of new technology is concentrated in the same "core" sectors: machinery and instruments, electrical and electronic, chemicals and transport. This is much less than the proportion accounted for by these sectors in manufacturing value-added.

➨ In all "core" sectors, the main focus is on product innovations that get adopted in a wide range of user sectors. In this sense, products in these sectors embody and diffuse "pervasive" technologies.

➨ The main user sectors within manufacturing are textiles, food and paper and printing. However there has been an increasing trend in the use of innovations in sectors outside manufacturing: agriculture, mining, construction, utilities, transport and services.

➨ Inter-sectoral differences in productivity growth are best explained by the use of technology, as compared to its production, or production plus use.

These studies so far have two limitations, one statistical and one conceptual:

➨ they do not measure satisfactorily the development of software technology, where the service sector is becoming an important source of new technology;

➨ they are static and descriptive. They offer no insights into how sectoral linkages evolve over time. This is because the unit of analysis is restricted to *product* sectors, whereas the activities leading to dynamic change are executed by *firms* on the basis of their *technologies*. Firms and technologies often straddle product sectors in important ways: for example, automobile firms often develop - and even make - capital goods for their automobile production. The accumulated technologies in firms help define possible future directions of technical change, and inter-sectoral relations.

Finally the studies outlined thus far do not capture the formal and informal co-operation related to the production and diffusion of technological knowledge between firms within the same industry and those in related industries. This is the subject of the next section.

TECHNOLOGY-RELATED COLLABORATIONS AMONGST FIRMS

This section is concerned with reviewing some of the main studies that have focused on the systematic measurement and analysis of collaborations amongst firms in the development of new technologies, products and processes. Such collaborations can be formal (subject of an agreement) or informal, they can involve horizontal (firms in similar lines of business) as well as vertical (suppliers or customers) relationships. Formal collaborations can take on many forms from simple licensing to more complex arrangements based on technology sharing and joint development agreements. They also include equity joint ventures where a separate entity is created and its ownership is shared by partner firms.

The reasons for entering into such arrangements include the need to reduce the cost and risk of new technological development especially in industries such as pharmaceuticals and commercial aircraft where R&D and other associated costs have increased rapidly in recent years. At the same time firms in a wide range of sectors have had to integrate developments in new fields such as biotechnology and information technologies (Granstrand et. al (1997)). Underlying some alliances is the need to rapidly penetrate foreign markets as product life cycles become shorter, and others, especially those between users and suppliers, are based on the need to formulate technical standards. Public funded programmes aimed at encouraging industry partnerships in R&D, such as the EU Framework Programmes, are also a stimulus to collaborative activities.

Literature-Based Counting of Alliances

One of the most widespread method of mapping inter-firm collaborations is based on gathering information on technology-based co-operative alliances (or agreements) through reviews of newspapers, journal articles, specialised books, corporate annual reports and other industry sources. This is the methodology that has been used to construct one of the most extensively used databases, the MERIT-CATI database, which contains information on nearly 13,000 agreements involving over 6,000 parent companies (Hagedoorn and Schakenraad (1990) and Hagedoorn (1995)). Amongst policy makers (OECD (1992), National Science Board (1993 and 1996), and EC (1997)) these data have been used to show that (a) there has been a big increase in inter-firm collaboration especially in new fast-growing areas such as biotechnology and information technologies and (b) a substantial proportion of such collaborations are inter-national.

However the literature-based counting of alliances suffers from one major drawback in that it relies entirely on collaborative activities reported and publicly announced in the various news sources. There are two main sources of bias inherent in such a methodology: bias against the recording of (a) those events that are only reported in non-English (national) sources, and (b) those involving smaller firms. Also caution needs to be exercised in interpreting the growth in the number of recorded collaborations which may simply be due to increased coverage of such deals as they become the focus of increasing attention.

Our own concern in this paper is with the ways in which the data on collaborative agreements have been systematically used to map inter-firm knowledge transfers. The most notable in this respect are the recent studies by Mowery et. al. (1996, 1998)) which examine how collaboration changes the relationship between a firm's technological portfolio and those of its alliance partner(s). They trace the relationship between the technological portfolios of partner firms using citation patterns in their patent portfolios. When the US Patent and Trademark Office grants a patent, the examiner produces a list of 'prior art' on which that patent is based. This includes a list of relevant prior patents which can be used an indicator of the technological lineage of that patent. Thus as Mowery et. al. (1996)) put it "As $firm_i$ acquires technological knowledge from its partner in an alliance, $firm_j$, we should see a higher rate of citation of $firm_j$'s patents in new patents applied for by $firm_i$". They apply this methodology to a subset of US firms engaged in bilateral joint ventures in the mid- 1980's, as recorded in the MERIT-CATI databank, to examine the role of knowledge in collaborative activities of firms. The results show that:

➨ Absorptive capacity (Cohen and Levinthal (1989)) is important: a given firm's ability to absorb technological knowledge from its alliance partner depends on the degree of the pre-alliance technological overlap between them.

➨ Firms that engage in collaborative activities have a higher degree of complementarity in their technological portfolio compared to a similar sample of 'non-collaborators'.

➨ In terms of the effects of such activities, they identify two patterns: firstly, where partner firms become (increasingly) similar to each other in terms of their technology portfolios as a result of collaboration, and secondly, where partner firms become more specialised in their portfolios, i.e. the similarity between them decreases. The former applies in more cases than the latter.

Such studies examining the role of knowledge within alliances and the effects of participation on the technological capabilities of firms on a larger sample of alliances hold much promise for future fruitful work.

Patents and Citations

There are a number of other ways in which data on patents and citations have been used to map different dimensions of inter-firm technology flows. For example information on inventor addresses from the front page of the patent have been used map the geographic distribution of citations (Jaffe et. al. (1993)). This work shows that technological linkages are geographically localised, i.e., patents cite other patents from geographically localised sites with (statistically significant) greater frequency than other patents from more distant sites. However further possibilities using these data remain largely unexplored. For example obtaining information on the nationality of the assignee of each patent would enable us to address policy relevant questions at the EU level such as: To what extent do EU firms utilise EU based technology (i.e. cite patents of other EU firms)? Do foreign firms build on EU technology (i.e. cite EU based patents)?

Another very little researched dimension of patent data concerns the analysis of patents that are filed by two or more companies (joint patenting) to map inter-firm collaborations. Rocha (1995) uses information on the product group and nationalities of a small sample of firms involved in joint patenting at the European Patent Office to map horizontal and vertical linkages as well as inter-national linkages.

Firm-Level Surveys

A more comprehensive approach to mapping inter-firm technological collaboration is contained in: (a) large scale firm-level innovation surveys such as those conducted in the various EU countries and sponsored by the EC (Community Innovation Surveys (CIS)), and (b) other surveys such as PACE (and Yale) which are addressed to large R&D performing companies. Part one of the IDEA project contains a thorough evaluation of both of these methodologies and hence in this paper we will concentrate more on the use of these data sources in terms of mapping inter-firm technology flows.

The CIS database contains answers to 3 sets of questions which are relevant: (a) on channels of acquisitions/ transfer of technology, (b) sources of information, and (c) R&D co-operation. In principle these data are available for a large set of firms (some 40,000) across many industries, size categories and 13 EU countries. In a recent report for the European Innovation Monitoring System (EIMS in DG XIII), Bosworth et. al. (1996) have explored some of the dimensions of these data. The main results of their research are:

➨ Internal sources of knowledge are generally the most important across firms of all sizes, industries and countries

➨ Importance of both internal and external sources of information increase rapidly with increases in firm size

➨ In general, firms make use of a wide range of channels for acquisitions/ transfer of technology

➨ R&D co-operation is more widespread amongst 'high' technology sectors compared to "low" technology sectors and amongst large firms compared to small firms

➨ Co-operative arrangements are much more common with local (regional) than national or international sources.

However there remain a number of other policy relevant questions that could be addressed with the information from CIS. For example the mapping of the differences and similarities between (a) the most innovative and the least innovative firms (using the data on R&D intensity and innovation intensity) and (b) the most successful and the least successful firms with respect to economic performance (measured by sales of new products or exports), in terms of sources of knowledge, and patterns of collaboration. The aim would be to make intra-sectoral comparisons taking the size of the firm into account.

The PACE (Arundel et. al (1995)) and the Yale (Klevoric et. al.(1995)) surveys also contain information on the sources of external technical knowledge of firms. Unlike the CIS, these surveys were addressed to R&D managers of large firms in Europe (PACE) and the US (Yale). In general both surveys come to similar conclusions regarding the relative importance of knowledge sources across industry. Thus the results of the PACE survey show that at the aggregate level technical analysis of competitor's product (or reverse engineering) is the most important source followed by knowledge gathered from independent suppliers, affiliated firms and independent customers. There are wide variations across industrial sectors, e.g., suppliers are a very important source of knowledge in the automobile sector but the least important source in pharmaceuticals. The PACE data has also been used to analyse the relative importance of national and international sources. The main conclusion is that after controlling for differences in industrial structure there are major differences between EU countries in the importance of domestic versus foreign sources of knowledge. In general, firms from smaller countries are less reliant on domestic sources than those from larger countries such as UK and Germany. Moreover knowledge interactions with sources in other EU countries are more important than those with the US and Japan.

INTERACTIONS BETWEEN FIRMS, UNIVERSITIES AND PUBLIC RESEARCH INSTATES

From a public policy perspective some of the most important interactions in the system of innovation are those between publicly funded basic research and technological activities. In this section we examine the nature and extent of the linkages (flows of knowledge, skills and competencies) between research carried out in universities and other public institutions and technological activities carried out in business firms. Empirical studies in this area are based on three main types of methodologies:

- Case studies
- Bibliometric analysis based on patents and scientific publications
- Firm Level Surveys such as PACE, Yale and CIS

Case Studies

A variety of case studies have traced how academic research contributes to technological problem-solving (Brooks (1994); Gibbons and Johnston (1974); Faulkner and Senker (1995); Hicks (1995); Meyer-Krahmer and Schmoch (1997); Rosenberg (1992), Sequeira and Martin (1997); Stankiewecz (1986, 1994)). The main channels and mechanisms of such contributions can be summarised as follows:

- ➨ **Useful knowledge inputs**, where academic research leads directly to prospects of application (e.g. X-rays, lasers).
- ➨ **Engineering design tools and techniques** - including modelling, simulation and theoretical prediction - have become central features in the design and testing of complex technological systems. These methods are often developed in academic engineering departments, and sometimes generate research programmes in related and more "academic" disciplines like mathematics.
- ➨ **Instrumentation** - products like cathode ray tubes were first developed as laboratory instruments, and techniques developed in academic laboratories are centrally important in today's bio-technology.
- ➨ **Trained scientists and engineers** are considered by many business practitioners as the primary benefit of academic research, since such training brings with it skills that can be applied well beyond the scope of the specific subjects of post-graduate research.
- ➨ **Background knowledge** - industrial practitioners are often less interested in the contents of the published papers of academic researchers than in the tacit skills and experience that underlie them. Scientific publications by industrial and other practitioners are partly devices for signalling and identifying potentially relevant expertise to the academic community.
- ➨ **Membership of national and international professional networks** - trained scientists and engineers bring to technological problem-solving "knowledge of knowledge" - in other words, membership of often informal networks that enable them to draw on the knowledge of other scientists and engineers, including those beyond national boundaries.
- ➨ **Spin-off firms** based on knowledge accumulated and discoveries made in universities.

Thus some contributions of academic research to technological practice will be *direct*, when such research leads to applicable discoveries, engineering research techniques (such as computer simulations) and instrumentation. Others will be *indirect*, when academic research training, background knowledge and professional networks contribute to business firms' own problem-solving activities - in particular, to the experimental engineering research, design practice, production and operation that will be mainly located within the business firms. Moreover the relative importance of the direct and indirect contributions will vary considerably across industrial sectors and research fields.

Bibliometric Analyses

One of the ways in which some of the direct contributions of basic science research to technological practice have been analysed is by means of bibliometric methods. Two types of data have been used to map such interactions: scientific publications and citations from large scale bibliographic databases and citations to scientific publications contained in patent documents.

Published papers in scientific and technical journals contain two information items that can be used to trace knowledge flows and that can describe the linkage structure, the direction and intensity of those flows. First, many papers are based on scientific co-operation and are written by researchers working at different institutions. The institutional addresses contained in those co-authored papers provide an explicit indicator of a linkage between those institutions. The citations in papers provide a second source of data for determining linkages and related knowledge flows. The institutional information on these cited publications, such as the names and country addresses provide indication of the direction and intensity of such flows.

Recent research using these data has shown that a substantial share of the papers in scientific and technical journals originate from industry (e.g. Hicks and Katz 1997, Godin, 1996; Tijssen et al., 1996). Many of those papers are co-publications listing both firms and universities or other public sector institutions as research partners. Further, a recent study by Tijssen and Van Wijk (1998) analyses these data for one important field, namely information and communications technologies (ICT), to map national, EU-level and international linkages. It shows that the highest proportion of such linkages are domestic. However compared to US and Japan, EU publications are less focused on domestic collaborations, but that a lot of these collaborations are with other EU companies. Further within the EU there is a relatively low share of (a) inter-firm collaborative publications in general, and (b) public/private collaborative papers in some areas of ICT such as Computers.

Interactions between science and technology have also been analysed using citations to scientific literature in patent documents. One of the most important pioneering analyses using these data was by Narin and Noma (1985) who showed the strong dependence of patents in biotechnology in the early 1980s on knowledge published in contemporaneous scientific papers. More recently, Narin and his colleagues have developed a much richer database covering citations in all US patents and used it to map the mix of scientific knowledge fields that underlie technological development in various industries (Narin and Olivastro, 1992). They confirm the closeness of the chemical industry to chemical science, the electronics and instruments industries to physics, and the petroleum and mining industry to the earth sciences. They also show the fields of chemistry, physics and engineering are important knowledge inputs across most manufacturing sectors, whilst the fields of clinical medicine, biomedical research and biology concentrate their inputs in the chemicals, pharmaceuticals and food industries.

Narin and colleagues have very recently taken their analysis one major step forward by systematically identifying more than 100,000 journal papers cited in US patents, matching them with more than 3,500 major US publishing institutions, and identifying where possible their funding sources (Narin et al., 1997). Their main conclusions relevant to this paper are as follows:

"Seventy-three percent of the papers cited by U.S. industry patents are public science, authored at academic, governmental, and other public institutions; only 27 percent are authored by industrial scientists. A strong national component of this citation linkage was found, with each country's inventors preferentially citing papers authored in their own country, by a factor of between 2 and 4. (...) The cited U.S. papers are from the mainstream of modern science; quite basic, in influential journals, authored at top-flight research universities and laboratories, relatively recent, and heavily supported by NIH, NSF, and other public agencies."

In other words, useful published research (as reflected in citations by US patents) tends to be publicly funded, national and high quality[2].

In the UK, Anderson and his colleagues (1996) have also undertaken a small-scale study of US patenting in human genetic technology that identifies cited papers of British origin. They show

[2] This confirms the results of earlier research using an interview-based methodology by Mansfield (1995).

that main funding sources for the research for these papers were the UK research councils and private foundations. They also found that Britain's significant contribution to patent-cited papers was not matched by a equally significant contribution to the related fields of US patenting.

Firm-Level Surveys

The most systematic analyses of the linkages between publicly funded basic scientific research and technological activities are based on the PACE and Yale surveys which were addressed to R&D directors of large EU and US based firms, respectively. They both contain information on the direct and indirect contributions of the output of basic research as well as the on the importance of specific fields of science to industrial sectors.

One of the key findings of the studies based on the Yale survey (Klevorick et. al. (1995)) is that there are major differences between the role of science as a *general pool of knowledge* and the role of *specific results* emerging from university research. The number of industries where R&D directors judged the former to be very important in contributing to recent technological advances were three times higher than those where the latter was judged to be very important. Thus one of the conclusions of Klevorick et. al. (1995) is that "overall, university-based research in a (particular scientific) field is reported as much less important to recent technological advance than is the overall body of science in that field". The Yale survey also contains information on the linkages between specific scientific fields and industrial sectors, some of which are well-known: e.g., biology with food and drugs, physics with electronics, and metallurgy with metal products. However, it also reveals others that are more surprising such as those between mathematics and computer science and the motor vehicles industry, where modelling and simulation as well as computer aided design are important in new product development.

The PACE survey of EU based R&D performing firms contains additional information on the importance of domestic versus foreign sources of knowledge as well as on the specific methods of obtaining such knowledge (such as publications, conferences and joint research etc.). One of the main findings of the analysis based on these data is that at the aggregate level the interactions with domestic public sector research (in universities and elsewhere) are much more important than those with foreign sources. This leads Arundel et. al. (1995) to conclude that "the public research infrastructure is one of the most important national assets for supporting innovation". More detailed data shows the existence of some differences according to nationality and industrial sector. Thus in the pharmaceuticals sector, where the US has a particularly strong public sector research base in medical and health sciences, US sources are rated as relatively more important compared to the average for all industries combined. The results by nationality show that for French and Italian firms interactions with universities and other public research are relatively less important and for German firms are relatively more important.

CONCLUSIONS

The above review has shown the progress that has been made over the last ten years in the measurement and analysis of knowledge flows between the various institutions involved in "systems of innovation". This has involved both more imaginative use of existing data (such as patent statistics and data on scientific publications and citations) and the gathering of new datasets by means of firm-level surveys (CIS, PACE and Yale) and other techniques (MERIT-CATI databank on alliances). Very often the most interesting results have emerged from studies that have sought to combine some of these measures (for example patent citations and strategic alliances) to examine the nature, extent and effects of knowledge interactions.

The results discussed in sections 2-4 relate to two related subjects that are of major relevance to policy making at both the national and the EU level:

➨ The continuing debates about the nature and extent of *globalisation of science and technology* (EC (1998)). Both the bibliometric and the survey-based evidence shows that there is a strong national bias in linkages between business practitioners and basic research in universities and public institutes. In our view this reflects the fact that such linkages involve the transmission of often tacit (i.e. non-codifiable) knowledge through personal mobility and face-to-face contacts, which are necessarily constrained by language and geography.

➨ Nature and extent of *contribution of academic research to technological practice.* The evidence indicates that a major part of the contribution of academic research is not *directly* through the provision of immediately applicable ideas, discoveries or information, but *indirectly* through the adoption -by technological problem-solvers working within business firms - of skills, techniques, instrumentation and professional networks created through academic research.

These results suggest that the one of the major goals of national and EU-level policy towards innovation should be to develop and maintain an internationally strong public sector research base. Moreover, such a research base should not concentrate on a few areas of directly applicable scientific knowledge but be broadly based and closely linked to postgraduate training and education. However, the success of this policy prescription depends crucially on the direction of the causal links between developments in national science and in national technology (Pavitt (1997)). Do they run from a national science base that creates the ideas, discoveries, skills, techniques, and instrumentation that the national technology system can then exploit? Or do they run from the national technology system that creates both demands on - and resources for - the national science system? There is little direct evidence on the direction of this causality, but as Pavitt (1997) argues, systematic time series information from patents and publications could be used to examine whether the growth of technology precedes and stimulates the growth of science. Moreover the data by scientific field and technology class could be used to relate the evolution in the patterns of scientific strengths and weaknesses to the evolution in the patterns of specialisation in technology.

Thus studies which are based on the combined use of a range of publicly available measures such as patents and publications will continue to be important in improving our understanding of the nature, extent and effects of knowledge interactions between institutions involved in "systems of innovation". At the same time the information form the CIS surveys could also be used in new ways such as in analysing the linkages between innovation and economic performance of firms and their patterns of collaboration and sources of knowledge. Finally new possibilities could also be opened up by developing new indicators such as those based on the stocks and flows of technical personnel employed in industry and services.

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