Jointly published by Akadémiai Kiadó, Budapest
and Kluwer Academic Publishers, Dordrecht

Scientometrics,
Vol. 54, No. 2 (2002) 193–212

Tracing knowledge flows in innovation systems

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This paper gives an overview of quantitative approaches used to study the science/technology linkage. Our discussion is informed by a number of theoretical approaches that have emerged over the past few years in the area of innovation studies emphasizing the exchange of actors in innovation system and a shift in the division of labour between publicly funded basic research and industrial development of technology. We review the more quantitative literature on efforts made to study such linkage phenomena, to which theorizing in the science policy area has attributed great importance. We then introduce a typology of three approaches to study the science/technology linkage – patent citation, industrial science, and university patenting. For each approach, we shall discuss merits and possible disadvantages. In another step we illustrate them using results from studies of the Finnish innovation system. Finally, we list key limitations of the informetric methods and point to possible hybrid approaches that could remedy some of them.

Background

Over the past few years, we could observe tendencies in innovation studies and related fields to put considerable emphasis on systemic view. There has been a shift of perspective towards interaction between the elements of innovation systems. (See, e.g., *Nelson* (1993), *Lundvall* (1992), *Granberg* (1996), OECD (1997).) There is considerable qualitative evidence of a trend towards an emerging triple helix of overlapping and intersecting activities by academic and industrial actors. The emergence of concepts like the 'academic entrepreneurs' and 'entrepreneurial university' reinforce this notion (*Etzkowitz* and *Leydesdorff*, 2000; *Etzkowitz* et al., 1998). Furthermore, science policy analysts postulated that scientific knowledge is produced in an application context of Mode 2 knowledge production (*Gibbons* et al., 1994). (See also *Ziman* (1994) who points to developments towards an increased perceived need for accountability. *Henderson* et al., (1998) highlight the increased industrial interest in academic research that contributed to growth in industrial funding of academic research, the desire of many universities to exploit new sources of income,

0138–9130/2002/US $ 15.00

and the growth in academic basic research advances in areas that appeared to have significant industrial applications, when discussing influence the increased patenting and licensing activity in universities.) Oversimplifying somewhat, policy concepts shifted towards a short-term Return-on-Investment logic (*Kealey*, 1998).

Increasingly, analysts have embarked on efforts to demonstrate technological, if not industrial, utility of scientific research. While some efforts were based on interviews or surveys, (for instance, *Senker* et al. (1998)), a considerable number of inquiries used bibliometric tools to explore the science-technology linkage. This paper reviews some of these more analytical efforts.

Exploration of science-technology interactions

As *Sirilli* observes, "we have no explicit model capable of determining causal relations between science, technology, economy and society in a single synthesis." (*Sirilli* (1998)). Referring more specifically to the relation between science and technology, *Verbeek* and his colleagues acknowledge the theoretical understanding that has been developed but point to the lack of quantitative studies of the area when they say:

> "… there has been quite some qualitative understanding of the linkage between science and technology. Yet until the '90 there has been very little quantitative data to specifically characterise this relationship or to pinpoint the subject, national, international and temporal aspects of the coupling between science and technology" (*Verbeek* et al., 2001, p. 26).

The status quo of S&T studies calls for more informetric studies that provide a more comprehensive picture of the complex S&T interactions. In other words, both quantitative and qualitative measurements are essential for performing a balanced analysis.

Definition of 'science' and 'technology'

Before introducing various approaches to study exchange processes at the interface between science and technology, it seems necessary to clarify the definitions. The analyst has to be clear as to how he or she defines these entities. In many, more formal studies, patents are considered a representation of technology, while papers are viewed as representations of science. Traditionally, companies patent more than they publish, and university researchers publish usually more than they patent. As *Pavitt* reports, business firms are granted about 80% of all patents, and many of the remaining 20% are granted to individuals who are owners of small firms (*Pavitt*, 1998a). Looking at publications, *Hicks* has established the reverse pattern. Academics publish more than do their colleagues in industry (*Hicks,* 1995). In such a situation, with most of the scientific papers published by academics and most patents held by (and originated in) industrial companies, the tendency to associate the academic sector with science and the industrial sector with technology is only natural. However, in this paper, we shall follow *De Solla Price*'s distinction between *papyrocentric* science and *papyrophobic* technology. According to him, science and technology differ substantially in their central activities due to different ultimate objectives that motivate those activities (*Price*, 1965). Scientists publish to maximize their visibility and recognition in their respective community. On the other hand, the technologist's objective is to construct or design a proprietary artefact or process. Based on this distinction, this study understands science as publication-directed activity and technology as a process that leads to patents rather than publications.

Scope of this study

In the broader context of innovation, one can distinguish essentially four types of data that are generally available for analysis (*Smith* et al., 1998):

- Firstly, there is data on R&D inputs, collected in the OECD economies according to the procedures and categories described in the "Frascati Manual".
- Secondly, there is patent data, the most important body of which consists of the records of the US Patent Office and the European Patent Office.
- Thirdly, there is bibliometric data on patterns of scientific publication and citation.
- Finally, there are various new types of data seeking to directly measure or indicate innovation processes across sectors: their inputs, outputs, objectives and so on.

In addition to these major sources, analysts draw often on 'ad hoc' data sources to explore specific research issues.

We shall not present an overview of the entire range of methods of analyzing the above mentioned data. As we are interested in exchange processes between science and technology, we do not focus on intersectoral flows within the domain of technology (for an overview, see e.g., *Patel*, (1998)). For the same reason, we shall not deal with the classical bibliometric indicators either (*Moed* (1996), for instance, presented an overview with regard to those indicators).

Formal approaches towards the interface

As *Smith* and colleagues pointed out patent citation analysis is the most popular analytical approach to investigate how science and technology relate to each other (*Smith* et al., 1998). However, theoretical work and more qualitative studies suggest that it might be useful to explore the technological aspects of university research and the scientific activity in industrial firms to get a more accurate picture of the science/technology interface (systems approaches and work on the triple helix are to be mentioned here, in particular). Figure 1 gives an overview of three different aspects of science-technology interactions:

(a) the overall connection between the bodies of science and technology, as exemplified by the patent citation connection,
(b) the industrial science connection, exemplified by publication activity of industrial researchers in business firms, and
(c) the technological aspects of scientific activity, as exemplified by patenting in universities.

For each of the above approach, we shall discuss merits and possible disadvantages.

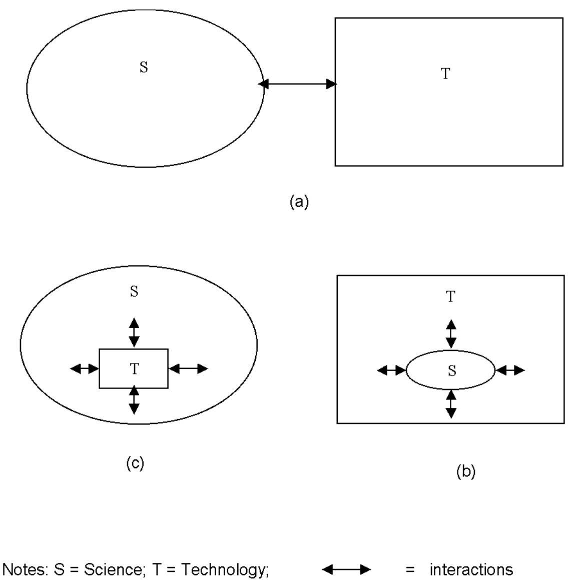

Figure 1. Three approaches to science-technology interactions in knowledge production.

Patent citation analysis. This section discusses the nature of patent citations and point to implications for their interpretation in terms of science/technology linkage.* Patent citations have become a popular indicator to track the assumed relation between publicly funded research and industrial applications. As *Smith* et al., establish, citations of scientific publications in patents are the most used indicator for measuring knowledge flows between science and technology (*Smith*, IDEA 5, pp. 123-124).

In general, this indicator has been used to analyse:

- the extent to which patent applicants and examiners utilise research findings,
- the nature of the cited research activity (whether the citations are to basic or applied research, to a narrow or wide range of scientific fields, to old or new papers),
- the performers of the cited scientific literature.

Often, analysts interpret the citation data in a direct fashion. Even though acknowledging that the old ‘linear model’ is “simplistic and highly inaccurate”, (*Narin*, 1997) they still appear to have basically a science-push understanding of the innovation process. This becomes apparent in the rhetoric they use to describe the nature of the science-technology relationship that is established by patent citations to scientific research papers. For instance, they postulate ‘science dependence’ of certain technologies, *Carpenter* (1980), and *Meyer* (2000, 2000a).

Recent research reminds us, though, that patent citations are inherently different from paper citations. Unlike scholarly citations, preferences in patents “are the result of a highly mediated process that is legally and socially shaped” (*Meyer*, 2000a, p. 100). The patent examiner – a party external to the inventive process – determines and selects the citations patent bibliometricians count in their studies mostly. Consequently, citation frequencies vary depending on the country in which the patent examination is carried out. As a result, patent citations must be viewed as an indicator of mediated science-relation of technology.

* Note that the length of time between the publication of scientific articles and patent applications is another, even though a far less frequently applied indicator of science-technology linkage. The mainstream literature considers the parallel development of publications and patents can be considered a strong indication for a close interaction between science and technology. Measuring the length of time in which an issue appears from the scientific publications to patents may provide an indication of structural aspects of knowledge diffusion in this particular field. *Narin* and *Noma*’s 1995 paper on biotechnology patents and citations can be considered the most prominent example of this approach. However, there are considerable methodological problems with this indicator, some of which are related to the nature of the patent citation process. Some of these aspects will be addressed in this paper. For a more detailed discussion, see *Schmoch U.* (1993), *Carpenter* (1980), and *Meyer* (2000, 2000a).

Even though one central implication is that causal links between publicly funded science and technology are hard to establish, a number of policy-applications are at hand. In particular, one can distinguish three major applications of patent citation analysis: First, following the general science orientation of fields over time by revealing a web of science and technology linkages. This application allows for observing potential governance shifts in certain S&T areas. Second, measuring the intensity of science and technology interaction. Third, tracking *potential* knowledge flows between scientific and technological fields. We have illustrated these applications elsewhere, drawing on our research on nanotechnology (*Meyer,* 2000b; *Meyer,* 2001).

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 to 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 (*Hicks* et al., 2001).

Human resources are an important factor in the diffusion of knowledge. For example, the movement of biotechnologists from pharmaceutical firms to agricultural firms would suggest the transfer of genetic engineering techniques from the pharmaceutical industry to agriculture (*Sirilli*, 1998, p. 17). These knowledge flows are indirect in nature. However, we must be aware that this is a connection that cannot be tracked by patent citations (see, for instance, the method development part in *Meyer*, 2001a).

Scientific publication in industry. This section explores approaches to study industrial publication activity as a measure of science and technology interaction. Scientific publications from large-scale bibliographic databases are recognized as a central source of information. They can be used to trace knowledge flows and can describe the linkage structure and intensity of those flows. A considerable amount of papers are the result of scientific co-operation and are written by researchers working at different institutions. The institutional addresses contained in those co-authored papers provide indicate links between those institutions (*Patel*, 1998).

It is usually believed that bibliometrics is not very well suited to measure industrial science since industry publishes relatively few scientific papers. However, tracking the publication activity of industrial companies can give an insight into the development of firm’s knowledge bases. An example for this is given in Figure 2, which describes the co-authorship links of Swedish pharmaceutical company Astra. The map presented can be a useful starting point to explore value, intensity, and reasons for university-industry cooperation. The map points to networks of exploration, where papers are co-authored with universities and university hospitals. Cooperation in this area even includes the national competitor, Pharmacia. The map also reports on collaboration in the area of clinical testing. Co-authored papers with general hospitals are likely to point to this type of activity. This analysis could be extended and deepened in combination with other tools, such as patent bibliometrics. At the industry level, it should be useful to track sectoral variance (see also our 'illustration').

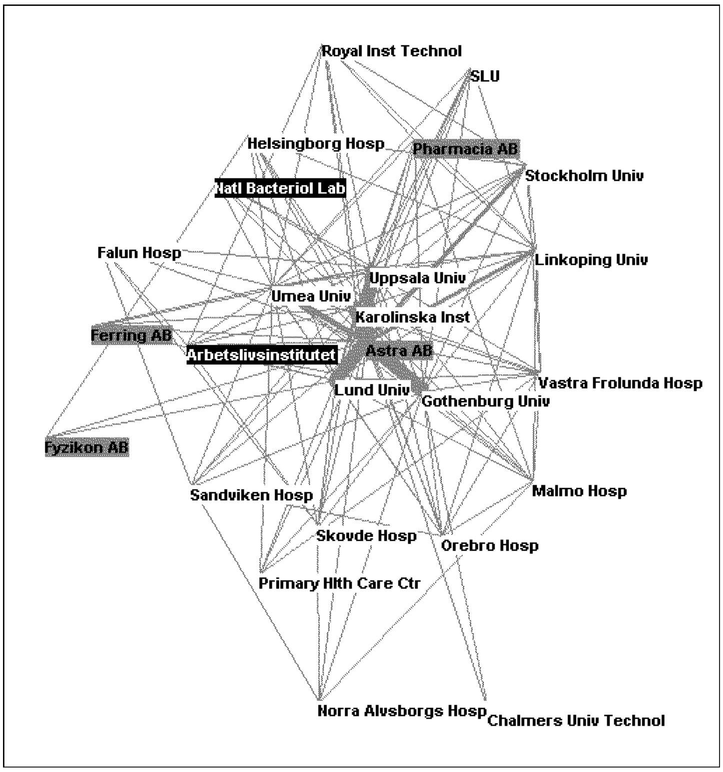

Figure 2. Co-authorship map of Swedish pharmaceuticals firm Astra (*Persson,* 2000)

Other research supports the notion that industrial publications are an indicator of the corporate knowledge base that positively contributes to the overall performance of the firm. In their study of pharmaceutical firms, *DeCarolis* and his colleagues use scientific publications as one of several measures – another is products under development, for instance – to track the performance of individual firms (*DeCarolis* et al., 1999). Citation counts of papers written by a firm's researchers appear to be in a positive relation with the firm's overall performance (*DeCarolis* et al., 1999).

Godin's study (1995) on research and the practice of publication in industries is an attempt to assess the usefulness of bibliometrics for measuring industrial scientific activities. The central aspects of the study include: (1) the importance of industrial publications, (2) the field of science privileged, (3) the level of science useful to industry (basic vs. applied), and (4) the science-technology relationships. The study draws attention to the fact that "science" needs to be better defined in science and technology studies, particularly in terms of disciplines useful to specific industries, as well as in terms of levels of research and in terms of the balance between the "doing" and using" science. What should be investigated in the future is the flow of knowledge between academics and industrialists. Despite all the rhetoric about the usefulness of academic research for industry, there have been surprisingly few studies attempting to establish who industry scientists cite (*Godin*, 1993, p. 602).

Drawbacks of the corporate science approach can be associated with its frequent focus on a set of firms or individual, large enterprises only. A central suggestion of research in the area of industrial publication is to track the flow of knowledge between academics and industrialists.

In this section, we referred to scientific activity in industry as measured by bibliometric indicators. This implies that the analyses of industry's or business firms' contributions to science we discuss here suffer necessarily from shortcomings generally associated with bibliometric indicators. The main problems include the following (*Sirilli*, 1998, pp. 14-15):

- the propensity to publish and cite varies in the various disciplines;
- works of great importance rapidly become part of common knowledge and are thus referred to in the literature without citation;
- citations may be critical rather than positive; however, it has been argued that even contested results make a contribution to knowledge;
- the various scientific fields are cultivated by groups of varying size, and thus the probability of being cited varies from sector to sector;
- the number of citations does not follow a linear rate in the course of time;
- the value of scientific work is not always acknowledged by contemporaries;
- available data bases are subject to some bias toward English language publications;
- papers represent only one output of laboratory-based activity. Scientific results related to information and software are not published to the same degree (*Hicks* and *Katz*, 1996).

Technological dimension of research activity. Patents are the most widely available indicator of output of technological activities. For many years patents counts have been used as indicators of technological achievement of firms and countries. Patents are a valuable source of information.

Over the past few years a considerable body of literature addressing the technological aspects of the universities has developed. Two reasons for studying university patents are emphasized (*Henderson* et al., 1998):

- patents are a unique and highly visible method of “technology transfer” (see, for instance also *Archibugi* and *Pianta* (1996),
- their accessibility allows for a more comprehensive analysis than is possible with either surveys or case study work.

A high share of patents on the part of scientific institutions can be considered a good indicator of a close relationship of scientific and industrial laboratories in the technology field analysed (*Schmoch,* 1997).

Coward and *Franklin* (1989) investigated the science-technology interface by combining two sets of quantitative data by defining the “science universe”, defining the “technology universe” and identifying the “intersect”. Three possible types of patent-paper intersections were investigated: (1) individual name matches between patent inventors and paper authors, (2) institutional name matches between patent assignees and organizations listed as affiliations by authors, and (3) examiner-cited literature references found in patents and base literature papers from the model. The authors conclude that author-inventor name matches appear to be the best approach.

However, there is a debate on definitional and interpretative issues on patents as measures of innovation. An example of the problems is *Rosenbloom*’s letter to the editor of *Research Policy* (*Rosenbloom,* 2000). (See also the reply by *Malerba* and *Orsenigo,* 2000.) In his letter, *Rosenbloom* challenges the terminology of *Orsenigo* and *Malerba*, who used the expression ‘innovator’ when they referred to organizations that developed new technology for which they obtained a patent. *Rosenbloom* reminds us of how *Schumpeter* defined innovators as entrepreneurs who bring new technology to commercial use, and compares this notion to a more recent use of the concept:

> “There is a world of difference. There was once a scholarly consensus that distinguished between invention and innovation. That consensus seems now to be eroding. For example, *Porter* and *Stern* (1999) recently proposed an “Innovation Index” (widely noted in the USA) constructed on the basis of a regression model in which the sole measure of national innovative capacity is a count of patents.

The article by *Malerba* and *Orsenigo* seems to be contributing to this unfortunate semantic trend. It might be argued that patent counts measure inventive effort, which in turn is highly related to innovative effort. Perhaps this is true, but I am not aware of persuasive evidence on the correlations between inventive effort and innovative performance. On the contrary, many patents are never put to use and the distribution of value among those that have some value is highly skewed (*Scherer*, 1999). Hence analysis of raw patent data is an uncertain indicator of innovation." … While I agree with the authors that patents remain «a valuable and unique source of data,» they provide data on technological effort, which is only one aspect of innovative activity. … Greater understanding of inventive activity clearly contributes to understanding of innovation as well, but that contribution is clouded if we lose sight of the differences between the two."

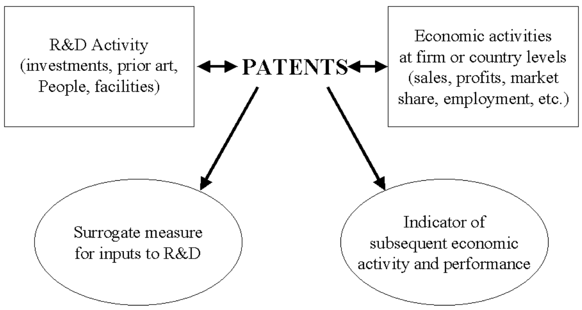

Figure 3. Patents as link between R&D and economic outcomes
(Source: *Geisler*, 2000), Figure 10.1. (p. 204)

The utilisation of data on patents to measure technical and scientific output raises a number of problems (based on *Sirilli*, 1998, pp. 7-8):

- the requisites for an invention to be patented and the type of examination it is subjected vary from country to country;
- the propensity to patent varies according to the industrial sector, size of firm and type of inventor (individual or employed in an organisation);
- it is not known what proportion of inventions is patented and thus one cannot say to what extent patenting reflects the entire area of inventive production;

- the "quality" and "value" of patents varies greatly (*Lanjouw* et al., 1996);
- insufficient data are available on the extent to which patents issued are in fact utilised (*Napolitano* and *Sirilli*, 1990);
- a significant proportion of patents are of the strategic type, i.e. applied for in order to forestall potential competitors.

Criticism suggests that patents granted to universities give a very partial and distorted picture of the contributions of university research to technical change (*Pavitt,* 1997). Some of the criticism is due to the fact that no systematic attempt has been made to track and follow up those patents not assigned to, but invented by researchers in universities. Case studies tracked the patenting of individual universities only. (See, for instance, *Wallmark* et al. (1988).)

Recent research, however, indicates that the number of patents invented in universities exceeds several times the number of university-owned patents. We shall present first results of this research in the following section.

Illustration

Our case study of the Finnish innovation system follows the three approaches discussed in the previous sections:

- Patent citation analysis;
- Examples of industrial scientific activities;
- University and academic patents.

This case is based on publication and patent data. Our analysis draws on a database of 61,000 Finnish SCI papers (1986-99) compiled by *Persson* and colleagues, a patent database of 6,800 Finnish US patents (1986-2000) as well as electronic personnel registries of the eight major universities of the country.

In the following subsections, we discuss each of the approaches and compare their respective results.

Strengths and Benefits	Weaknesses and Problems
• Patent databases have been in existence for many years • Patent data are relatively easy to manipulate • Patent data can be related to other economic/financial measures • Patent data have a similar structure as a legal document • Contain revealing information • Indicate levels of S&T effort • Similar items of information facilitate cross-industry and even cross-national comparison • Considered as a link between S&T an firm performance, patents offer an elegant way of establishing such a link • Patents are viewed as indication of technological achievements • Patents are viewed as measures of the knowledge-base • Patents are viewed as measures of the quality of S&T	• Patents do not always lead to commercial applications • Patents are only a small portion of the actual R&D and S&T effort • Patents reveal only selected information about S&T • Patentable inventions have become increasingly harder to discover • The link S&T-Patents-Performance is based on covariation methodology and lacks a description of the process and factors that impact this presumed link • There is a lack of a theory to explain how patents contribute to performance and to strategic advantages (except for the link to possibly monopolistic manifestations of the power from patent protection)

Figure 4. Patents as a S&T indicator
(Adopted from *Geisler,* 2000, pp. 207–208)

Patent citation analysis

Using the Bibexcel software tool, we carried out a matching procedure of our patent and publication data. All in all, 300 non-patent references – this is 4.41% of the Finnish patents – could be identified that linked Finnish science, as represented by our SCI publication database, and Finnish technology, as characterized by our patent databank.

Where they occurred, citations linked the scientific domains of biotech, medical, and cardiovascular research and the IPC classes A61, C07, C12, and G01. These results are not surprising since all fields of technology that have citation links to the scientific journal literature are said to be highly science-related.

Surprisingly, areas of high-technology, such as telecommunication and pulp & paper have only relatively weak connections with the journal literature. Given that Finland is viewed as a leader in these fields and also holds a considerable number of patents in these areas, one wonders if these areas are really not related to the science base at all. This is a point we shall take up below in our analysis of patenting by university researchers.

Industrial scientific publication activity

An analysis of the scientific publications documented that Finnish industry accounts for 2,700 or 4.4% of all SCI papers. This is a rather modest share, in line with expectations.

However, it is interesting to note that the number of papers authored in industry exceeds the number of patent citations (not even the number of papers cited) by a factor of nine. The firm-level data confirms the links drawn by patent citation analysis in so far as the most active firms in terms of SCI publications are mostly from the pharmaceuticals and biomedical sectors.

Yet the data also points to substantial scientific activity of firms outside these clusters. The Top 5 companies in scientific publication are:

- Orion (pharmaceuticals),
- Alko (alcohol monopoly),
- Neste/Fortum (energy),
- Leiras (pharmaceuticals),
- Wallac (bio/med).

The telecommunications group Nokia is the 6th largest source of scientific papers in Finland. Even though corporate science is relatively weak across the entire range of the economy, the leading firms reach the smaller technical universities in terms of publication activities.

In relation to above patent citation analysis it is interesting to note that 44-56% of industrial papers are co-authored with the university sector. Approximately 1,300 papers were published by researchers in industry in collaboration with their university colleagues. Compared to 300 patent citations, we find this linkage is relatively strong.

Also that the importance of industrial science varies with the respective sector. For instance, firms are relatively active in materials research (see Figure 5). In other fields there is far less industrial activity to be observed. Furthermore, if one compares sectoral maps across a range of countries, one can point to different co-authorship (network) configurations. We have done this for Finnish and Swedish materials science and engineering. It is instructive to observe the much weaker industrial participation in scientific publication activities in Sweden than we could observe in Finland.

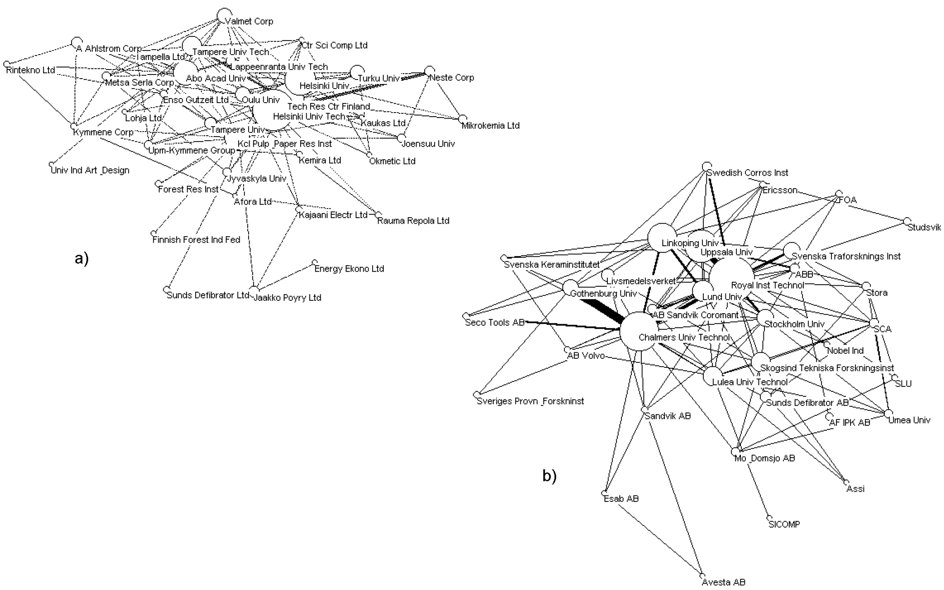

Figure 5. Co-authorship maps in Finnish (a) and Swedish (b) materials science and engineering (Data from *Persson* et al., 2000)

Public institutions, therefore, appear stronger in Sweden than in Finland. One can only speculate as to why this is the case – different orientations of the economies or firms, different industrial structures, etc. In any case, the maps appear to be a good starting point for further explorations.

Patenting by academic researchers

This analysis is based on our patent database and personnel registries of Finnish universities. We obtained electronic listings of the latter form all relevant institutions and carried out matching procedures using Bibexcel. The results of these procedures were name matches, which link inventor names in Finnish US patents with the listed names in personnel registries. We had to carry out validation procedures, contacting all potential inventors verifying if they are indeed the individuals who were listed on the patents. In 95% of the cases, we managed to reach our potential inventors.

The validation procedure identified 509 of some 6,800 Finnish US patents that were invented by individuals working in eight major universities. Also, this number is higher than the citation links that could be tracked from Finnish patents to Finnish science. The preliminary analysis of the data showed that the patent rankings of universities differ already from the citation ranking. We can identify a substantial amount of technological activity in universities that is directed at telecommunications, chemicals, pulp and paper. The analysis of university-generated patents allows us to point to different, additional links between university science and industrial technology.

Other observations are as follows:

- patents invented by university researchers appear to exceed by multiples the number of patents owned by the universities;
- a small group of key inventors are responsible for a considerable share of the patents, while only a small number of university researchers does patent;
- most of the patents appear to be assigned to established firms and not to be exploited by start-up companies;
- individual universities hold extra-ordinarily high numbers of patents that remain unassigned; in a single case up to 31% of all US patents granted and invented in that university did not have an assignee.

Comparison

If one compares the results of the three analyses, one notices that there is much more technological activity going on in university science and much more science performed in industry than there are patent citations between science and technology. There is only little exchange we could track by means of patent citation analysis, most of it in bio/medical technologies.

We could also track more scientific papers by industry than there are citations connecting any Finnish scientific publication with any Finnish patent, whether they were generated in academe or industry. It is also noteworthy that half of the industrial publications were co-authored with academics, thereby constituting a stronger connection between academic science and industrial technology than is established through non-patent references in patent documents. Also, there was considerable publication activity in fields where very few connections could be traced.

The third approach points to further connections outside the science/technology citation linkages. We could track a considerable number of patents linking academics to technology and industry also in fields, such as telecommunications, materials, pulp & paper. In this case, too, there are more university-originated inventions than citations.

Discussion

Arundel et al. postulated three qualities of what makes a good innovation indicator. In particular, innovation indicators should provide information that can meet three requirements (*Arundel* et al., 1998):

- Directly assist the development and implementation of policy actions. The need for indicators to *directly* assist policy means that the policy significance of each existing and potential indicator needs to be carefully scrutinised.
- Verify innovation theory as part of a continual process of testing and improving *theories of innovation*. The requirement for indicators to improve our understanding of the innovation process is based on the vital role of theory in interpreting empirical data.
- *Assist private firms and other institutions to develop and adjust their own innovation strategies*. The social and economic value of innovation indicators will be greatly enhanced if they are of direct value to innovators themselves.

But to what extent are the measures good indicators? Can they directly assist formulating and implementing policies? Are they of any use in testing and verifying innovation theory? And what is their value in supporting the development of innovation strategies at the organizational level?

This discussion, and especially the illustration, have demonstrated that none of the approaches presented can satisfy these requirements on its own. The analyst would miss significant points, parts of the puzzle, if s/he chose to neglect any one of the three approaches: patent citation, industrial science, or academic patenting analyses. In particular, we hope to have clarified that patent citation analysis is just one, and not necessarily the best way of tracking the science/technology interaction.

Looking at the various approaches and how they have been applied until recently, their method-driven character is quite apparent. Techniques from one field have been applied to another area without necessarily re-thinking the interpretation. Other approaches have been neglected for a variety of reasons even though they may be more instructive in studying the flows of knowledge between institutions of science and technology.

Method-driven approaches have been strongly criticized. For instance in the case of network research, *Rogers* criticizes the 'seemingly blind loyalty' of scholars to one network method or another –"whether or not that method best fits the particular research problem (*Rogers*, 1987)." As a result, *Rogers* postulates a

> "… triangulation strategy in which we compare several types of data (and methods of data analysis) about single social phenomena, each of which may provide a unique understanding that the other methods do not (*Rogers,* 1987)."

This applies also to our area. Future research on science-based technologies and innovation should pay more attention to the complex and multi-dimensional interaction between science and technology. The approach should be informed by a systems perspective, which integrates all three major aspects of interaction analyses. This might be achieved in conjunction with other analytical approaches, such as inventor-author relation approach, mapping of co-occurrences of publication and patent key words, (*Noyons* et al., 1994) and the parallel observation of patents and publications (*Schmoch,* 1997).

Efforts should not stop at the integration of metric methods but also transcend their own boundaries and be open for other extensions. Our case illustrated that the three approaches together cannot be more than a partial measure of science/technology interaction. For instance, knowledge flows embodied in human resource transfers cannot really be measured by above approaches. Innovative components of knowledge-generating activities are not covered either by tracking patents and linking them to scientific actors or literature. Patents and other metrics cannot give information, about the obstacles of university-industry collaboration, such as (*Landry* et al., 1996):

- disagreement over patent and licensing arrangements;
- restrictions over information dissemination;
- institutional differences such as culture, objectives and time frame;
- geographical distance between parties; career constraints;
- time required to coordinate collaborative projects;
- inefficiencies in the structural arrangements of collaboration and
- differing degree of intensity in the relationships between academic disciplines and industry.

These phenomena are too diverse to be captured in metrics. Combinations of formal and survey schemes may be more effective. The above discussion would suggest a 'hybrid approach' to study the exchange between science and technology. This includes following up commercial attempts (licensing, start-ups, etc.) by means of an inventor survey after the object approach. This way it would be possible to use the databank as a non-arbitrary basis for an inventor survey that could extend and augment the existing database.

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Received October 12, 2001.

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