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**The Fruits of Intellectual Production:
Economic and Scientific Specialisation
Among OECD Countries**

by

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Abstract

This paper brings together data from 14 OECD countries on scientific publications, patents and production specialisation to explore the relationship between economic and production specialisation for 17 manufacturing sectors. Since Marx, there has been a fundamental debate in economics about the link between science and the economic system. Marx argued that the developments in the science system are strongly influenced by changes in the economic sphere, whereas Polanyi argued that developments in science are largely independent of economic sphere. Using a panel data model and econometric estimations at the sectoral-level, the paper assesses the two positions and finds considerable support for Marx's position, that is, that scientific and production specialisation are, often, tightly linked.

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1. Introduction

This paper explores the relationship between scientific activities and economic specialisation. Since Marx, there has been a fundamental debate about the link between science and the economic system. Polanyi (1962) argued that the developments in the science system take place largely independent of economic factors, whereas Bernal (1939) saw the considerable potential for using the science system to shape the economic superstructure. Today, debates over the role of science-based innovation focus on the link between strength in fields of science and national competitiveness. For example, many authors argue that a strong science-base can help to improve national competitiveness (Pavitt, 2000). Yet there are few empirical studies that link the science base to the economic sphere. By establishing regularities and discussing the causality between economic specialisation and the strength of the pool of national scientific knowledge, across a number of advanced countries, this paper provides new evidence on the relationship between science and the sphere of production.

The research is based on the link between specialisation in scientific publications and economic activities at the national and sectoral level. In order to explore this link, we develop a concordance between 77 Institute Scientific Information (ISI) scientific fields and 17 manufacturing sectors using a database of industrial publications in the UK from 1981 to 1994. Scientific publications are seen to represent part of the knowledge base of the industrial sector, that is, the ideas and techniques that underpin economic development. Production statistics are taken to represent the sphere of economic activities. With our concordance between patterns of production and science, we explore the relationship between patterns of specialisation across 17 advanced OECD countries. The data used for the study are drawn from the ISI National Indicators on Diskette, SPRU BESST, the US Patent Office and from the OECD STAN databases.

The analysis shows that most industries draw from a wide number of scientific fields. We find that for many science-based and scale-intensive sectors, there is a statistically significant relationship between scientific activity and economic specialisation. This suggests that science and the sphere of production are, indeed, related. In this respect,

Marx was right. The analysis also shows that inter-industry differences matter greatly in determining the link between scientific and economic specialisation.

The organisation of the paper is as follows. Section 2 explores the relationship between science and the economic system, drawing from the work of Marx, Rosenberg, Bernal and Polanyi. Section 3 examines the empirical background to the study. Section 4 describes the method of the study and presents descriptive statistics about the scientific and economic specialisation across the sample population. Section 5 contains the econometric analysis and Section 6 concludes.

2. Theoretical Considerations

The relationship between science and the economy has come to the fore in recent policy discussions of the knowledge-driven economy. A central point of contention is that the way new ideas are generated, diffused and used in the economic system can have important implications for national competitiveness. New economically useful ideas are often generated through investments in the science system and many OECD countries have made new efforts to try to link their science system to the economic needs of industry (OECD, 2001).

This interest in the relationship between science and production is not new, however. In 1841, List commented:

[t]here scarcely exists a manufacturing business which has no relation to physics, mechanics, chemistry, mathematics or to the art of design. No progress, no new discoveries and inventions could be made within science by which a hundred industries and processes could not be improved or altered” (1841/1959: 162).¹

Yet, as Rosenberg argued, Karl Marx was one of the first to explore the link between science and the economic system in detail and in theory.² In his and Engels’ Communist Manifesto, Marx argued that the material conditions of production create intellectual production (Marx refers to science as intellectual production). Engels stated “from the beginning, the origin and development of the science has been determined by production” (Engels cited in Rosenberg, 1976: 128). The changes in the sphere of production shape knowledge production by determining what is necessary, useful or valuable. Rosenberg summarises Marx’ (and Engels’) position as:

Science does not grow or develop in response to forces internal to the science or the scientific community. It is not an autonomous sphere of human activity. Rather, science needs to be understood as a social activity which is responsive to economic forces. It is man's (or women's) changing needs as they become articulated in the sphere of production which determines the direction of scientific progress. (1976: 128).

Despite this extreme position, Rosenberg and Freeman contest that the demand argument of Marx (and Engels) is often overemphasised in the literature on technical change (Rosenberg, 1976; Freeman, 2001). Marx recognised that science had only become tightly linked to production when science itself reached a particular state of development. It was through the rise of specialisation (i.e. the increasing division of labour) and the application of science to the production process that the link between science and the sphere of production was created. When production was re-organised on the basis of the needs of capital, capital was able to use the instruments of science and technology to, in turn, reshape its production process. This process of mutual support and development created a *dialectical* relation between science and the sphere of production. Marx saw that the ability to “apply science to the productive sphere turns upon industry's changing *capacity* to utilise such knowledge” (Rosenberg, 1976: 129, emphasis in original). It is the capability of the productive sphere to use knowledge that creates and ensures the dialectical relation between the two spheres of activity.

It would be difficult for even a strong proponent of Marx's views to deny that there is some degree of autonomy to internal factors in the development of a science system. Past attempts to ascribe major scientific breakthroughs to economic factors have often failed to persuade. As pointed out by Chris Freeman (2001), historical studies in science have shown that neither the origins of particle physics nor the origins of molecular biology can seriously be explained in terms of economic factors or connections with industry. Their subsequent development and their applications in the electronics industry and in the pharmaceutical industries certainly owed a great deal to the interactions between the science and the productive sphere. Yet, Marx did highlight the important role of the productive sphere in shaping scientific activities.

How then, is science shaped by the sphere of production? Rosenberg (1976), lists several possible mechanisms:

- direct financial support;
- the expectations of returns motivates individuals to solve a particular scientific problems;
- the needs of industry act as a powerful agent in calling attention to specific problems;
- normal production activities throw up physical evidence of great importance to scientific development;
- hegemonic control, i.e. shaping of social norms, views and goals.

An updated and expanded version of Marx's view of science was reflected in the work of J. D. Bernal (1939). Bernal argued that governments could use science for achieving social and economic goals. In this respect, Bernal is often seen as the intellectual father of the field of science policy (Freeman, 1999). Bernal saw the potential to use intellectual production means for expanding and creating material choices, e.g. governments could choose which areas to fund and thus achieve social and economic objectives. Science could be harnessed to help achieve social and economic goals, linked to the needs of the sphere of production. Bernal argued that left to itself the science system might be misdirected away from important areas of research with considerable social and economic value. He called for planning of scientific investigations to ensure that science was pointed in the direction of social and economic change. He drew attention to the problem of a high proportion of research funding being concentrated in military-related research, lowering the social utility of research funding in general (see Freeman, 1999).

In contrast to Marx and Bernal, Polanyi (1962) argued that the science system operated largely independently of the government and societal control. He defended the "Republic of Science". In this view, intellectual production must be divorced from the sphere of production. New ideas are developed through the insight, experience and experimentation of individuals and teams working within the institutions of science, Polanyi argued. These processes of discovery, review and experimentation cannot be controlled or shaped by purely social or economic objectives. For Polanyi, science

seeks fundamental understanding outside of material conditions of society. To achieve their goals of fundamental discoveries, scientists need to be separated from the social factors. They need to stand apart from society. “The soil of academic science must be exterritorial in order to secure its control by scientific opinion” (Polanyi, 1962: 67). Polanyi argued that Bernal’s approach for making science closely follow social and economic objectives would have a pernicious impact of scientific development, limiting the development of new ideas. He stated:

[y]ou can kill or mutilate the advance of science, you cannot shape it. For it can advance only by essentially unpredictable steps, pursuing problems of its own, and the practical benefits of these advances will be incidental and hence doubly unpredictable (Polanyi, 1962: 67).

Moreover, Polanyi argued that many social and economic objectives are well beyond the capabilities of scientific research.³

The tension between the Polanyi’s Republic of Science and Bernal’s instrumentalist views of science has been reflected in science and technology policy choices of OECD governments. Many advanced OECD countries have attempted to strike a balance between the desire to use science for social and economic objectives, on one hand, and the belief that science should be left partly independent from social needs and economic objectives, on the other hand. Vannevar Bush’s *The Endless Frontier* strongly supported a Polanyist approach to science policy, calling for the science system to be separated from economic and social control (Barfield, 1997).

Despite this call for independence, most governments have not separated science from social and economic control. In the US and other OECD countries, science systems in the post-1945 era were managed on the basis of a compromise between the Polanyist and Bernalian approaches to science policy. A considerable portion of science funding was linked to targeted programmes or goals, especially in the military and health-related areas, but at the same time, substantial funding was provided to the science system to be independently allocated. In the case of targeted and open research programmes, peer review has remained the primary method for determining research funding at the individual project level, a Polanyist approach to allocation of funds. However, when attempting to balance funding across competing areas of research,

governments have often used Bernalian approaches to guide and shape the scientific inquiry, such as Technology Foresight.⁴

The general balance between these two modes of funding has shifted over time, but overall the research systems in the OECD have been responsive to societal needs. This is, in part, reflected in the majority of public funding for research being concentrated in practically-oriented disciplines, such as engineering, medicine and agricultural science (Pavitt, 2000).

However, since the early 1980s, the post-1945 compromise has come under increasing strain. Many argue that new forms of knowledge production reshape the link between science and the economic system and make the post-1945 compromise untenable (Gibbons *et al.*, 1994). They point the rise of the knowledge-driven economy, arguing in the economic system is becoming more and more dependent on science. The traditional role of actors in the knowledge production system is blurring and knowledge production is becoming pluralistic with a variety of public and private actors creating and competing in new knowledge-based industries. The independence of science decision-making should no longer be taken as a given.⁵

As part of this questioning of the post-1945 compromise, there has been an increasing emphasis on the use of the science system to support economic development. This new approach sees opportunities for universities act as engines of economic growth, providing ideas to fuel economic development (Etzkowitz *et al.*, 2000). Governments often wish to maintain greater control and management of research. Science is too important to be left to the scientific community is a common argument. Government action is required to ensure the science system delivers on its economic potential. New policy instruments, such as Technology Foresight, are seen to provide opportunities to find a better integration between academic and industrial research objectives (Martin and Johnston, 1999).

3. Empirical Background

This shifting policy environment reflects on-going debates in innovation studies over the role of demand and supply in shaping innovation. Early work on patents by Schmookler (1966) suggested that innovation was largely shaped by market demand.

Boosting demand would also boost innovation and therefore improve scientific progress. Rosenberg and Mowery challenged this conclusion, arguing that many areas of science are immune to demand and the impact of science on technology and therefore on the economic structure has been profound. They argued that there is an interactive coupling between market demand and scientific and technological possibilities in the process of innovation (Mowery and Rosenberg, 1979; Freeman and Soete, 1997: 200).

In order to overcome this debate, Nelson argued that it is important to realise that science and the sphere of production co-evolve, that is science and economic system mutually reinforce each other over time (Nelson, 1994). For example, strength in a particular industrial sector might lead a government to invest in a research programme associated with that sector. Nelson describes the general process of institutional development and adaptation as innovation systems' response to opportunities opening up both in science and industrial practice. Nelson argues that in most countries a division of labour between different actors in the innovation system has developed with some groups focusing on knowledge production and skills generation, while others focus on exploitation and dissemination. In Nelson's model of co-evolution, it is, however, difficult to disentangle the changing roles of science and economic activity over time. For those who see science becoming increasingly important for innovation, the co-evolution argument is not nearly sufficient. They wish to go well beyond this historical perspective as they see opportunities for pro-active strategies to harness the economic potential of science.

A key part of the argument that science is increasingly important for innovation is the rise in the number of citations in industrial patents to academic research. Narin *et al.* (1997) found a three-fold increase in the number of citations to academic research in US patents over the 1990s. This shift toward higher numbers of citations of academic research in industrial patents suggests to many the increasing science-dependence of technology and *vice-versa*. Hicks *et al.* (2001) show that the highest growth in citations to academic research in industrial patents has been located in health-related sectors. However, in information technology-related sectors, there is limited evidence of an increasing science-dependence. Hicks *et al.* conclude that in information technology industries the pace of technical change is too fast for the pace of scientific

research and publication, indicating considerable inter-sectoral variety in patterns of interaction between the science and the production sphere.

For Narin *et al.* and others the increasingly prevalent links between science and technology suggest that in the knowledge-driven economy, scientific research plays an increasingly important role in shaping patterns of growth. Investments in science can play a leading role in support of industrial innovation, especially in health related sectors, and they can help nations to secure a dynamic, successful economy.

The increasing importance of science in industrial practice is often linked to changes in the nature of research and development strategies among large firms. More and more organisations are subcontracting, collaborating and internationalising their R&D budgets. These new R&D strategies seek to use universities as listening posts for new ideas and technological possibilities (Christensen, 1997). At the same time as industrial firms are reaching out to universities for new ideas, universities are seeking support from industry. The rise of university patenting and other forms of intellectual property indicate this general trend (Hicks *et al.*, 2001; Mowery *et al.*, 2001).

Many universities have created incubators, venture capital funds and science parks with the direct purpose of increasing their private income. These activities can also be seen as increasing the impact of research on the sphere of production. Etzkowitz *et al.* see the rise of the entrepreneurial university, increasingly raising funding from private sources and freeing itself from public control. Pavitt also argues that fundamental changes in the nature of technological development via new information technologies have created possibilities for new science-based firms to emerge from universities. Technical changes in the tools of engineering design (rapid prototyping, simulation and optimisation tools) create opportunities for science-based university firms to explore technical concepts and products, to act as product developers and to offer specialised technical services to industrial practice (Pavitt, 2000).

Despite this enthusiasm for linking science with opportunities in the sphere of production, the empirical evidence on the economic benefits of publicly funded research is mixed (Salter and Martin, 2001). It has been difficult for economists and others to find a direct link between support for research and industrial innovation. Part

of the problem is related to the problem of measurement. Often the links between research and economic activities are subtle, varied and indirect. It remains difficult, if not impossible, to assess the economic impact of a piece of research in the short term. Mowery and Rosenberg argued that knowledge from science is transferable to production, but often it is limited in its range of application (Mowery and Rosenberg, 1979: 237). Pavitt argues that “the route from discovery to application is often long and tortuous, involving the movement of knowledge, techniques and instruments from one discipline to another” (Pavitt, 2000: 11).

There are, moreover, considerable differences across industries in the importance of science for innovation. In pharmaceuticals and biotechnology, the link between science and economic activities appears to be quite strong. The findings of research in the life sciences can often have direct economic implications. This is demonstrated by a high number of university spin-offs in these sectors and by the high number of academic citations in industrial patents (Hicks *et al.*, 2001). Yet, in other industries, such as auto manufacturing and aerospace, the links are much more varied. In their study of technological opportunities, Klevorick *et al.* (1995) found considerable inter-industry differences in the importance of university research as sources of innovation. Leading users of industrial research were the largely science-based sectors, such as pharmaceuticals and chemicals. In non-science-based sectors, the link between research and innovation was usually mediated by the transfer of skilled graduates from universities into practice and through the transfer of new scientific ideas into engineering school educational programmes (Nelson and Rosenberg, 1994). Given the fact that a strong link between innovation and economic performance has been confirmed for a large share of industrial sectors (e.g. Soete, 1981; Amable and Verspagen, 1995), the above mentioned studies point in the direction of a particularly strong relationship between relevant national scientific performance and national economic specialisation in the case of science-based sectors.

In order to better understand the contribution of different fields of science to innovation, Klevorick *et al.* breaks down the contribution of science into different disciplines. Their study lists 14 different scientific disciplines and, for each industry, respondents were asked to indicate the importance of these different disciplines for their innovation processes. The results confirm the finding that industrial practice

often relies on several different disciplines. For example, auto-manufacturers use traditional engineering disciplines, such as mechanical engineering and more basic sciences, such as physics and mathematics. This empirical finding is supported by the Pace study. It also explores the use of different disciplines (10 disciplines) across different sectors in Europe. It finds that industries differ in the extent to which they draw from science and across different scientific disciplines (Arundel *et al.*, 1995).

Most studies in this area have, however, relied on indicators of science, such as papers and technology, such as patents. Few studies have linked indicators of science and technology to the sphere of production. Both the Yale and Pace studies show that industries draw from a variety of scientific fields and, in this sense, all industries rely on a broad range of knowledge to underpin their activities. Yet the analyses contained in Klevorick *et al.* and in Arundel *et al.* do not provide a detailed picture of the links between individual sectors and particular disciplines of the science. Both studies use a limited range of disciplines. They also rely on the ability of individual firm respondents to assess the importance of these disciplines to their firms' innovation processes. In some cases, the number of respondents per industry was modest. For example, in the Klevorick *et al.* study, in almost half of the industries sampled the number of respondents was two or less (Klevorick *et al.*, 1995). In our approach, we attempt complement these survey-based approaches by using aggregated industrial statistics and more detailed data on scientific publications.

The use of industrial scientific publication data for describing the character of the knowledge underpinning innovation in particular sectors has become relatively common. Narin and Olivastro (1992) and Godin (1996) used publication data to map the scientific knowledge base of individual sectors. Hicks argued that firms use scientific publications to signal their competencies to others, to gain access to scientific networks and to recruit skilled graduates (Hicks, 1995). By exploring these publications, it is possible to develop an understanding of individual sector's knowledge base and to explore the changing role of science in the innovation process. However, few of the studies using industrial publications have broken down these publications to a low level of disaggregation. For these researchers, broad patterns of publication provided sufficient information for describing the general scientific knowledge base of individual sectors.

More detailed work on linking patterns of publication to industrial sector has recently been completed by Arundel and Geuna (2000). Using a mixture of survey and publication data, they demonstrate the key role of the domestic science base in influencing patterns of innovation across a wide variety of sectors. The data also show that the pharmaceutical sector has the most internationalised scientific knowledge base of different industrial sectors (Arundel and Geuna, 2000). Arundel and Geuna use a matrix of industrial sectors by fields of science based on expert opinion. Our approach is similar, but it is based on the actual industrial publications by sector.

To sum up our discussion on the relationship between the economic and the scientific spheres across nations, we (i) expect that relevant (to each industry) scientific activity co-evolves with economic (production) specialisation. Moreover, we (ii) expect firms in industrial sectors to draw on a variety of scientific disciplines, and (iii) believe that there is a strong link between relevant scientific performance (measuring the ability to produce science at a world class level) and production specialisation in science-based industries. Since the relationship between the two spheres is much more indirect, when dealing with non-science-based industries, we (iv) expect that there is a positive correlation between relevant scientific *specialisation* (not necessarily reflecting world-class science, but only indicating a relatively strong position within the given country) and production specialisation in some of the non-science-based industries.

4. The data

The bibliometric data used for the analysis are drawn from the ISI database and from the SPRU BESST database on UK publications (for more information on BESST database see Hicks and Katz, 1997). Based on the SPRU BESST database's data on the publishing activity by UK firms over the period 1981-1994, we conjecture the relevance of 77 scientific fields for 17 manufacturing sectors. This procedure hinges on the assumption that if firms in particular sectors publish papers in particular fields of science, then they — at least partly — do it because they have, and wish to maintain, an “absorptive capacity” in the relevant scientific fields. The ISI database contains publication data for 105 fields of science for 176 countries over the period 1981-1998. Since we want to use the BESST database for linking up the STAN and the ISI databases, and since the BESST database does not follow the original ISI

nomenclature, we end up with 77 fields of science (for more details, see Sub-section 4.1 below). The economic data are taken from the OECD STAN database (1998 edition), while patent data are obtained from the US Patent Office. Since the STAN database is very incomplete after 1994, we use data from all sources over the period 1981-1994. Moreover, we use the information for 17 countries — the maximum number of countries in the STAN database with relatively complete data for all of our variables.

This section will first spell out how we have constructed the concordance, linking fields of science to production statistics. Moreover, since the concordance table can in itself be revealing when exploring this link, we also devote some space to the analysis of some of the properties of the concordance table (in Sub-section 4.1). We then (in Sub-section 4.2) explain how the table is used for constructing the variables representing scientific strength and specialisation to be used in the subsequent econometric analysis (in Section 5). All other variables to be used in the econometric analysis are presented as well.

4.1. The concordance table linking science and production

As argued above, by exploring patterns of publications by firms in an individual sector, it is possible to understand how firms draw and exploit different pools of scientific knowledge. In order to construct our concordance, we separated out the scientific publications of industrial firms in the UK research system. For this analysis, we used 292 firms, each of which had at least 10 scientific publications. We then divided these firms into 17 industrial sectors (following the STAN classification), drawing from an existing classification developed by Hicks and Katz (1997) and based on the Financial Times list of companies. For each firm, we explored their main line of business, using annual reports and business publications, and placed that firm in the industrial sector that best corresponded to its profile of production. We were able to classify 172 firms according to this method. Those firms where information about their main line of business was unavailable were removed from the analysis.

Table 1 lists the number of publications by industrial sector and the numbers of firms included in the analysis. Due to differences between the ISI list of disciplines and the list of disciplines used in the BESST database, it was necessary to integrate the two

different lists of disciplines in a master list. The aggregation was completed by collapsing some groups into each other based on the authors' estimates of where these disciplines overlapped. For example, the BESST database had six disciplines under computer science and the ISI had one. In this case, we collapsed the six BESST disciplines into the ISI framework. By following this procedure, we ended up with 77 fields of science, organised according to the ISI nomenclature

The database is based on data from the UK alone. It would be useful in the future to use a wide spread of industrial publications drawn from a variety of countries. Not only would this ensure a greater reliability of data, it would also be possible to vary the time period for the analysis. Data on the citations were removed from the analysis. Citation data are highly skewed and it would require a different approach to the one used here to integrate it into the analysis. However, future research in this area might find citation data to be a useful complement to the total number of publications.

Table 1 demonstrates that each sector is highly multidisciplinary; that is, it is active in a wide number of different scientific fields. Industrial chemicals appears to be the most active industrial sector with the broadest number of publications across the scientific fields (75). Industrial chemicals is followed by pharmaceuticals (73) and stone, clay and glass (65). Motor vehicles appears to be the least diverse industrial sector, but even here it is possible to find publications across 19 scientific fields. The Herfindahl Index provides a measure of the concentration of scientific papers across the different scientific fields for each industry. The value of the index is high when the firms of an industry are publishing in a few scientific fields and/or when the publications are concentrated in a few scientific disciplines. In contrast, the value of the index is low when the firms of an industry are publishing in many scientific fields and/or when the number of publications are equally spread across the scientific disciplines. Petroleum refining and industrial chemicals again appear to be the most diverse industry using this measure, whereas electrical machinery and communication equipment were the most concentrated. Using a simple correlation between the number of papers and the degree of concentration, we found no relationship between the total number of papers by an industry and the diversity of the industrial sector scientific knowledge base (p -value equal to 0.78). There are some sectors with a limited number of scientific publications, yet they remain relatively broadly spread

Table 1: Spread of industrial scientific publications across scientific disciplines by industrial sector

	Number of Scientific Fields (c=77)	Herfindahl Index	Number of publications	Number of Firms
Petroleum refineries	57	0.065	2424	11
Industrial chemicals	75	0.086	6395	20
Non-electrical machinery	30	0.096	134	4
Other transport equipment	36	0.109	239	7
Fabricated metal products	25	0.110	111	3
Rubber and plastics	38	0.112	251	5
Food, drink and tobacco	52	0.116	880	9
Aerospace	44	0.117	462	9
Pharmaceuticals	73	0.119	12478	46
Office machines and computers	39	0.132	315	9
Motor vehicles	19	0.150	41	2
Instruments	45	0.187	394	6
Stone, clay and glass	65	0.199	3629	20
Iron and Steel	20	0.249	165	1
Non-ferrous metals	21	0.254	118	2
Communication eq. And semiconductors	35	0.315	2354	6
Electrical machinery	40	0.405	2559	12

Note: The Herfindahl Index is calculated as $\sum_{i=1}^c (n_i / N)^2$, where c is the number of scientific fields, n_i the number of papers in field i and N is the total number of papers in all fields.

across a range of fields, such as non-electrical machinery.⁶ This suggests that even in sectors where the relationship between scientific research and industrial practice appears to be weak, as represented here by the number of publications, there is still a need to access research from a wide range of fields.

These findings stress the importance of a broad science base for supporting industrial innovation. The data confirm the earlier findings of a study of the pharmaceutical sector among OECD countries. Laursen (1996) found that scientific strength across all scientific fields appears to have a greater impact on shaping patterns of specialisation in the pharmaceutical industry than could be accounted for by specialisation purely in the life sciences field. This indicates the importance of the breadth of the science-base in shaping patterns of economic specialisation.

The data from our concordance table represent a challenge to science policy initiatives that attempt to support industrial innovation in a particular sector by investing in a narrow range of scientific disciplines. The data show that diversity is an essential

characteristic of industrial interaction with the science base. Industrial firms need, use and publish in a wide range of scientific fields. Research policies seeking to limit diversity and concentrate investments in a limited number of “strategic” fields of research, often with the explicit intent of supporting innovation in a particular sector, may find that these policies yield meagre results.

4.2. The variables

The dependent variable in our econometric analysis is Revealed Production Advantage (c.f. Balassa, 1965). The algebra can be set up as follows:

$$(1) \quad RPA_{ij} = (Y_{ij} / \sum_i Y_{ij}) / (\sum_j Y_{ij} / \sum_i \sum_j Y_{ij}),$$

where the numerator represents the percentage share of a given sector in national manufacturing - Y_{ij} is production of sector i from country j . The denominator represents the percentage share of a given sector in OECD17 manufacturing production. The RPA index thus contains a comparison of national production structure (the numerator) with the OECD17 production structure (the denominator). When RPA equals 1 for a given sector in a given country, the percentage share of that sector is identical with the OECD17 average. Where RPA is above 1 the country in question is said to be specialised in that sector and vice versa where RPA is below 1. However, since the RCA turns out to produce an output which cannot be compared on both sides of 1, the index is made symmetric, obtained as $(RPA-1)/(RCP+1)$; this measure ranges from -1 to +1. The measure is labelled “Revealed Symmetric Production Advantage” ($RSPA$).⁷

In most empirical studies on the determinants of international manufacturing specialisation (typically measured as trade specialisation) and performance, cost and technology factors have been identified as the major factors (Soete, 1981; Amable and Verspagen, 1995; Gustavsson *et al.*, 1999; Laursen and Drejer, 1999). When conducting an analysis of the relationship between national scientific specialisation and strength on the one hand, and economic specialisation on the other hand, it is therefore necessary to control for these “standard” factors.

Cost competitiveness is generally measured by either wages per employee or unit labour costs. Here we use unit labour costs since the level of wages *per se* can be

related to labour productivity and therefore its effects on production specialisation might be ambiguous. Our measure is defined as follows:

$$(2) \quad ULC_{ijt} = (W_{ijt}/VA_{ijt}) / \left(\sum_j (W_{ijt}/VA_{ijt}) / n \right)$$

where W_{ijt} is the wage sum of country j , in sector i , at time t , expressed in current prices and VA_{ijt} is value added in fixed prices; n is the number of countries.⁸ Since the RHS variable (and the other LHS variables) is measured in relative terms we divide by the average value of the 17 countries for each given time and sector.

Different contributions have used different proxies in order to measure technological specialisation. The most commonly used measures of disembodied technology are R&D and patent statistics: the former is better suited to capture the inputs to the innovation process while the latter is a measure of the innovation output. In this paper, we have chosen to work with US patent data, mainly because R&D data are only available for a more limited sample of countries. The technological specialisation variable therefore defined as in a similar way to the *RSPA* from above, but in this case the input to Equation (1) is not production, but instead US patents by sector, country and time. In this case we obtain the “Revealed Symmetric Technological Advantage”. In order to avoid problems of small numbers, it can be noted that the patents have been aggregated four years back, while using linear depreciation over time.

We include two measures of scientific activity relevant to our 17 industrial sectors: one variable measures the scientific strength (or performance), and another variable measures scientific specialisation. These two scientific variables are the key for our analysis. However, first we adjust for the unequal size of scientific disciplines by weighing the concordance table is by the size-distribution across the 77 scientific disciplines (based on the cumulated publications from the ISI database for all the relevant years). In this way we obtain an adjusted concordance table. The adjusted concordance table is used for calculating both scientific strength and scientific specialisation

In order to obtain the “relevant” scientific strength we calculate the share of publications by a given country (for a given year) in each of the 77 scientific fields

from the ISI database and normalise the obtained vector by the total population of the given country. Subsequently, the resulting vector is multiplied (element-wise) by the adjusted concordance matrix (77 fields of science x 17 industrial sectors). The variable is then subsequently calculated by adding up the 77 fields for each of the 17 industrial sectors. In this way we get a single figure measuring the “relevant” scientific strength for each industrial sector (labelled *SP*, i.e. short for “Scientific Performance”). The procedure is repeated for all years (14 years; 1981-1994) and countries (17 countries) .

The variable measuring specialisation relevant to each of the 17 industrial sectors is obtained by calculating a “comparative advantage figure” (analogous to Eq. 1) based on the ISI data. Subsequently, the obtained vector of specialisation is multiplied (element-wise) by the adjusted concordance matrix (77 fields of science x 17 industrial sectors). As in the case of scientific performance, the variable is then subsequently calculated by adding up the 77 fields for each of the 17 industrial sectors. However, since by following this procedure, we are likely to get countries “specialised” in all of the 17 industries, we normalise the result by calculating yet another comparative advantage figure, across the 17 industries. In this way we obtain the “Revealed Symmetric Scientific Advantage” (*RSSA*). Again, the procedure is the repeated for all years and countries .

5. Econometric analysis

Based on the variables described above the model to be estimated, it can be set up as follows:

$$(3) \ RSPA_{ijt} = \beta_{1i} + \beta_{2j} + \beta_{3i}RSTA_{ijt} + \beta_{4i}ULC_{ijt} + \beta_{5i}SP_{ijt} + \beta_{6i}RSSA_{ijt} + \varepsilon_{ijt}$$

where β_{1i} is a sector-specific effect and β_{2j} is a country-specific effect, and ε_{ijt} is the error term. Footsign *i* on the parameters indicates that the model is to be estimated while allowing the slopes to differ in the sectoral dimension. It can be noted that we do not want to make inferences concerning Granger-causality between the science variables and economic specialisation. Given the relative short time-period for which we have data, such an analysis would provide little information, since the co-

evolution between the economic and the science systems has happened over decades, and even in some cases over centuries.

We expect all parameters to have a positive sign, except for the parameter for unit labour costs. In the case of unit labour costs, the effect on economic specialisation can be ambiguous. From the point of view of production cost, we would expect high ULCs to lead to low specialisation in a given sector. However, as high wages might be associated with high skill levels, low wages might also lead to a low degree of specialisation (Amable and Verspagen, 1995: 200).

The results of the estimation of Equation 3 are displayed in Table 2. From the Table, it can be seen that technological specialisation (*RSTA*) is an important factor in explaining specialisation in terms of production, since the parameter for this variable is positive and significant for fifteen out of seventeen industrial sectors. Hence, it can be concluded that technology plays an important role for economic specialisation, not only in high-tech industries, but also in medium- and in some low-tech industries. Unit labour costs also play an important role in determining production specialisation, since ten parameters turn out to be significant at the ten per cent level (using a two-tailed test). Nine of the seventeen coefficients are negative, and six of these coefficients are significant (pharmaceuticals; rubber and plastic products; stone, clay and glass; iron and steel; non-ferrous metals; other transport equipment). These six cases are consistent with the view that high ULCs (part of production costs) lead to low specialisation in a given sector. Apart from pharmaceuticals, it can be noted that the six negative and significant industries are medium- to low-tech industries — industries normally thought to be cost-sensitive areas of production. Nevertheless, four coefficients are positive and significant (food, beverage and tobacco; electrical machinery; communication equipment and semiconductors; instruments). These results indicate that since high wages are likely to be associated with high skill levels, high skill levels may have led to a high degree of specialisation in these four industries. Three of the four industries are high-tech industries — industries in which skill levels are normally believed to play a major role.

For what concerns the science variables, it can be seen from Table 2 that the coefficients for scientific strength are positive and significant in ten out of seventeen

Table 2: Regression results explaining specialisation in manufacturing production over the period 1981-1994, across 17 OECD countries ($n=3628$)

	<i>RSTA</i>	<i>p</i> -value	<i>ULC</i>	<i>p</i> -value	<i>SP</i>	<i>p</i> -value	<i>RSSA</i>	<i>p</i> -value
Food, beverage and tobacco	-0.02	0.458	0.16	0.031	-0.13	0.007	0.67	0.000
Industrial chemicals	0.26	0.000	-0.04	0.170	0.13	0.001	0.49	0.000
Pharmaceuticals	0.21	0.000	-0.13	0.000	0.12	0.003	-0.35	0.017
Petroleum refineries	0.16	0.000	0.01	0.527	0.00	0.937	0.24	0.463
Rubber and plastic products	0.25	0.000	-0.09	0.001	0.10	0.007	0.76	0.000
Stone, clay and glass	0.01	0.612	-0.20	0.000	-0.22	0.000	0.61	0.004
Iron and steel	0.12	0.013	-0.21	0.000	0.00	0.936	0.74	0.000
Non-ferrous metals	0.41	0.000	-0.17	0.000	0.05	0.285	0.33	0.214
Fabricated metal products	0.16	0.000	-0.01	0.848	0.16	0.000	-0.03	0.912
Non-electrical machinery	0.53	0.000	0.11	0.127	0.22	0.002	-1.08	0.000
Office and computing machinery	0.57	0.000	0.00	0.932	0.28	0.000	-2.08	0.000
Electrical machinery	0.17	0.000	0.30	0.000	-0.22	0.000	0.12	0.530
Communication eq. and semiconductors	0.55	0.000	0.11	0.036	0.02	0.648	-0.68	0.002
Other transport equipment	0.17	0.027	-0.39	0.000	0.27	0.000	-2.29	0.000
Motor vehicles	0.83	0.000	0.19	0.071	0.31	0.000	-0.53	0.136
Aerospace	0.17	0.032	-0.07	0.481	0.52	0.000	1.70	0.041
Instruments	0.16	0.048	0.26	0.000	0.44	0.000	-0.41	0.211

Note: Adj. $R^2 = 0.61$. Sector and country specific constants included, but not reported for reasons of space. *P*-values calculated on the basis of White's heteroscedasticity consistent standard errors.

cases (industrial chemicals; pharmaceuticals; rubber and plastic products; fabricated metal products; non-electrical machinery; office and computing machinery; other transport equipment; motor vehicles; aerospace; instruments). Moreover, the coefficients are positive and significant in the case of six industries (food, drink and tobacco; industrial chemicals; rubber and plastic products; stone, clay and glass; iron and steel; aerospace) for the scientific specialisation variable. Hence, these results show — in general and as expected — that most industries with strong science-based properties⁹ (industrial chemicals; pharmaceuticals; office and computing machinery; aerospace; instruments) rely on the availability of relevant scientific strength (scientific output at a world-class level) held by the given country.¹⁰ However, a number of scale-intensive sectors also appear to need relevant scientific strength (fabricated metal products; other transport equipment; motor vehicles). The common denominator for the industries which rely on scientific specialisation (rather than on performance) appear to be that these industries are in general either natural resource based (food, drink and tobacco; stone, clay and glass; iron and steel) or scale intensive (industrial chemicals; rubber and plastic products).¹¹

6. Conclusions

Using a variety of data sources, this paper has explored the relationship between scientific activity and economic specialisation. We have found a link between scientific activity and economic specialisation across a number of industrial sectors. This finding upholds Marx's view that intellectual production is strongly related to material production. Production specialisation is indeed related to scientific activity. The research provides evidence for the dialectical or co-evolution view of the relationship between science and production. Our findings further strengthen the view that the science system is responsive to industrial and social needs. Derek de Solla Price's metaphor of the relationship between science and technology as "dance partners" can be equally applied to science and production.

In particular, we found that for most science-based and for some scale-intensive sectors, there is indeed a statistically significant association between relevant scientific *performance* and economic specialisation. We take this as an indication of a rather direct link to the underlying science-base for what concerns these industries. In addition, we found a significant and positive relationship between relevant scientific *specialisation* and economic specialisation for most natural resource based industries and for some scale-intensive industries. For these

industries, we take the results as an indication of a much more indirect link to the scientific system.

Our analysis also showed that industries draw from a wide variety of scientific disciplines and the diversity of the science base can play an important role in explaining production specialisation. We have suggested that policies aiming to support particular industries by making investments in a narrow range of disciplines commonly associated with those sectors will yield only limited results. A broad approach that involved balancing academic research funding across a wide number of disciplines may ensure a higher degree of industrial relevance.

There are many limits to our approach given both the problems with the available datasets and to our macro-approach to studying the links between scientific and production specialisation. The industrial publications are for one country, the scientific specialisation data run from only 1981 to 1994 and the production specialisation indicator is a partial reflection of the production sphere. Further refinement of the method is required.

The paper points to new areas for research. One area for further development is cross-country comparisons. Our current approach uses country dummies to discount the role of country-specific features. It would be useful in the future to explore the patterns of specialisation within and between countries. In particular, it would be useful to assess the match between individual country's science system and its patterns of production specialisation. A second line of inquiry could involve exploring changes over time in patterns of specialisation to see if science systems are becoming more or less close in structure to the patterns of production specialisation. The current data make these time series estimates extremely difficult. A longer time series and more advanced econometrics might make such an analysis possible. If possible, such an approach would indicate whether science leads production specialisation or vice-versa. A third approach would be to explore the roles of different fields of science in explaining production specialisation. It might be possible to find a number of leading fields of science that have the capacity to alter patterns of specialisation across countries.

Endnotes

- 1 We are grateful to Chris Freeman for this reference.
- 2 Marx's was not the only one to focus on the link between science and the economic sphere. Alexis De Tochville commented extensively on the role of economic sphere in shaping the role of science (Pavitt, 2000).
- 3 A modern restatement of the Polanyist position in science policy is contained Dasgupta and David's new economics of science (Dasgupta and David, 1994). Dasgupta and David argue that there are considerable advantages in allowing the science system a high degree of independence in the allocation of funding. They highlight the open and universal character of the science system and, like Polanyi, they stress the competitive forces operating in the science system than ensure an efficient and effective allocation of social resources. In support of the Polanyi's Republic of Science, they suggest that attempts to interfere with the institutions of the science system could have a pernicious impact of the future ability of the science system to generate, support and sustain knowledge production and distribution.
- 4 Freeman argues that in historical debate between Polanyi and Bernal about the nature of science, the Polanyist position lost the argument (Freeman, 1999). Polanyi and his followers were forced to agree that since much of the funding for science came directly from government, government would have a considerable role in shaping the process through which research funds are allocated across different areas of research. The Polanyist model also breaks down when it becomes necessary to distribute funding across general programmes of research because few scientists have a detailed knowledge about the relative merit of research in fields outside their own. Therefore, some mechanisms are required to support the allocation of science funding across competing areas of research. Government also retains some degree of responsibility for the operation and effectiveness of the science system given its fiduciary responsibilities for the management and allocation of public funds in general (Freeman, 1999: 118-119).
- 5 There is an open debate within the science policy community about Gibbons *et al.* approach (see David, 1995).
- 6 The techniques used in this paper do not consider the role of the research as the boundaries of existing disciplines. Often research at the interstices of existing disciplines is responsible for the significant economic impact. Because our data set is arranged by the ISI disciplines, we are not able to explore research operating across the boundaries.
- 7 For discussion of this topic, see Laursen (2000).
- 8 Note that our sample includes four-digit ISIC sectors for which no constant price value added are available (pharmaceuticals, computers and office machines, electronics, other transport, aerospace). For these sectors, we use the corresponding three-digit (implicit) price indices for calculating constant price value added.
- 9 For a classification of the STAN sectors into the Pavitt taxonomy (supplier dominated, science-based, scale-intensive and specialised suppliers), see Laursen and Meliciani (2000).
- 10 In fact, all science-based industries, but communication equipment and semiconductors, appear to rely on relevant national scientific performance.
- 11 It can be noted that the two significant science-based industries, aerospace and industrial chemicals, both have science-based as well as scale intensive properties (see Laursen and Meliciani, 2000: 708).

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Danish Research Unit for Industrial Dynamics

The Research Programme

The DRUID-research programme is organised in 3 different research themes:

- *The firm as a learning organisation*
- *Competence building and inter-firm dynamics*
- *The learning economy and the competitiveness of systems of innovation*

In each of the three areas there is one strategic theoretical and one central empirical and policy oriented orientation.

Theme A: The firm as a learning organisation

The theoretical perspective confronts and combines the resource-based view (Penrose, 1959) with recent approaches where the focus is on learning and the dynamic capabilities of the firm (Dosi, Teece and Winter, 1992). The aim of this theoretical work is to develop an analytical understanding of the firm as a learning organisation.

The empirical and policy issues relate to the nexus technology, productivity, organisational change and human resources. More insight in the dynamic interplay between these factors at the level of the firm is crucial to understand international differences in performance at the macro level in terms of economic growth and employment.

Theme B: Competence building and inter-firm dynamics

The theoretical perspective relates to the dynamics of the inter-firm division of labour and the formation of network relationships between firms. An attempt will be made to develop evolutionary models with Schumpeterian innovations as the motor driving a Marshallian evolution of the division of labour.

The empirical and policy issues relate the formation of knowledge-intensive regional and sectoral networks of firms to competitiveness and structural change. Data on the structure of production will be combined with indicators of knowledge and learning. IO-matrixes which include flows of knowledge and new technologies will be developed and supplemented by data from case-studies and questionnaires.

Theme C: The learning economy and the competitiveness of systems of innovation.

The third theme aims at a stronger conceptual and theoretical base for new concepts such as 'systems of innovation' and 'the learning economy' and to link these concepts to the ecological dimension. The focus is on the interaction between institutional and technical change in a specified geographical space. An attempt will be made to synthesise theories of economic development emphasising the role of science based-sectors with those emphasising learning-by-producing and the growing knowledge-intensity of all economic activities.

The main empirical and policy issues are related to changes in the local dimensions of innovation and learning. What remains of the relative autonomy of national systems of innovation? Is there a tendency towards convergence or divergence in the specialisation in trade, production, innovation and in the knowledge base itself when we compare regions and nations?

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There are at present more than 10 Ph.D.-students working in close connection to the DRUID research programme. DRUID organises regularly specific Ph.D-activities such as workshops, seminars and courses, often in a co-operation with other Danish or international institutes. Also important is the role of DRUID as an environment which stimulates the Ph.D.-students to become creative and effective. This involves several elements:

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- participation in research projects
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