Cambridge Journal of Economics 2005, **29**, 289–308
doi:10.1093/cje/bei032

The fruits of intellectual production: economic and scientific specialisation among OECD countries

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This paper brings together data from 17 OECD countries on scientific publications, patents and production, to explore the relationship between scientific and economic specialisation for 17 manufacturing industries. Since Marx, there has been a fundamental debate in economics about the link between science and the economic system. Marx argued that the needs of production shape scientific developments and that science has become a factor of production, whereas Polanyi argued that developments in science are largely independent of the economic sphere. Using a panel data model and econometric estimations at the industry level, the paper derives some hypotheses from the two positions and finds that, while the overall evidence on the link between national production and scientific specialisation is mixed, it is important to have high levels of relevant to-the-industry scientific strength *per capita* in order to be specialised in science-based industries.

Key words: Scientific specialisation, International economic specialisation, Bibliometric data
JEL classifications: O31, C23

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. Marx argued that the economic sphere shapes scientific development, yet conversely Polanyi[1] (1962) suggested that the

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Manuscript received 4 February 2002; final version received 9 July 2003.

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*Copenhagen Business School and Tanaka Business School, Imperial College London, respectively. This paper has greatly benefited from suggestions and comments by Keith Pavitt, Aldo Geuna, Chris Freeman, Pablo D'Este, Pari Patel, Mike Hobday and three referees of this journal. An earlier version was presented at the ECIS Conference on The Future of Innovation Studies held in Eindhoven, 20–23 September 2001. Ammon Salter would like to acknowledge the financial support of the European Commission-sponsored projects NPRnet and Newkind and the ESRC-funded CoPS innovation centre. Keld Laursen would like to thank the Centre for Economic and Business Research for financial support. The usual disclaimers apply.

[1] Michael Polanyi—should not be confused with his brother Karl Polanyi, as the two fundamentally disagreed on the ability of the economic sphere to influence other spheres in society. Karl Polanyi's central viewpoint was that the development of capitalism was a historical anomaly, because, while previous economic arrangements were 'embedded' in social relations, in capitalism the situation was reversed—social relations are governed by economic relations (Polanyi-Levitt, 1990).

developments in the science system take place largely independent of economic factors. 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, 2001). 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 country and industry level. In order to explore this relationship, we develop a concordance between 77 Institute of Scientific Information (ISI) scientific fields and 17 manufacturing industries, 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 industry, 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, the 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. Moreover, we find that while the overall evidence on the relationship between national production and scientific specialisation is somewhat mixed, it is important to have high levels of scientific strength *per capita* in order to be specialised in science-based industries. 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. (List, 1841/1959, p. 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, p. 128). The changes in the sphere of production shape knowledge production by determining what is necessary, useful or valuable. Rosenberg summarises Marx's (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, p. 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 bound 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 bond between science and the sphere of production was created. When production was reorganised on the basis of the needs of capital, capital was able to use the instruments of science and technology, in turn, to 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, p. 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 science and the productive sphere. Despite this fact, Marx was among the first to highlight the tight bonds between the emerging science system and the productive sphere.

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[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, 2001).

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 as a 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, Michael 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 material conditions of society. To achieve their goals of fundamental discoveries, scientists need to be separated from 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, p. 67). Polanyi argued that Bernal's approach for making science closely follow social and economic objectives would have a pernicious impact on 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, p. 67)[1]

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[1] A modern restatement of the Polanyist position in science policy is contained Dasgupta and David's new economics of science (Dasgupta and David, 1994). 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.

In Figure 1, we attempt to represent visually the characteristics of the Marx–Bernal position. It shows that that the shape of the science system is created by its interaction with the productive sphere via the channels identified by Rosenberg. Central to the Marx–Bernal perspective is that the overall shape of the science system will conform to the overall shape of the economic sphere. In other words, the performance of the science system will match the performance of the economic sphere. This position is represented in Figure 1 by two overlapping and joined circles, indicating the common shape of activities in each sub-system of social activity.

Figure 2 draws from the Polanyi position, exploring the role of internal developments in science in shaping scientific performance. Here there is no direct link between the economic sphere and scientific performance. Endogenous factors and institutions within the science system, such as peer review, curiosity etc., play the central role in influencing the pattern of performance. There are some obvious links between economic sphere, such as government funding for science and industrial R&D activities. However none of these links is central to the shaping of the performance of the science system. The science system stands apart, driven by its own internal prerogatives and incentives. In Figure 2, the differences between the two systems are represented by differing shapes, a circle and a square.

The argument between Polanyi and Bernal (as illustrated in Figures 1 and 2) about the nature of science has been an important touchstone in the development of science and technology policy of OECD governments. The tension between the Polanyi's Republic of Science and Bernal's instrumentalist views of science remains unresolved, and it continues to be a source of debate within the scientific and science policy community. In order to chart a path between these two positions, many advanced

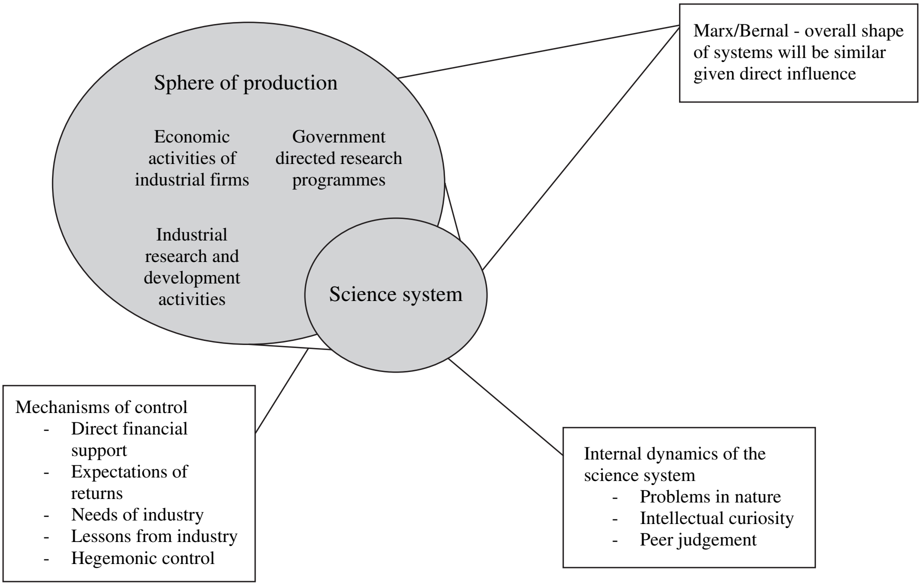

Fig. 1. *The bond between the production sphere and science system – Marx-Bernal perspective.*

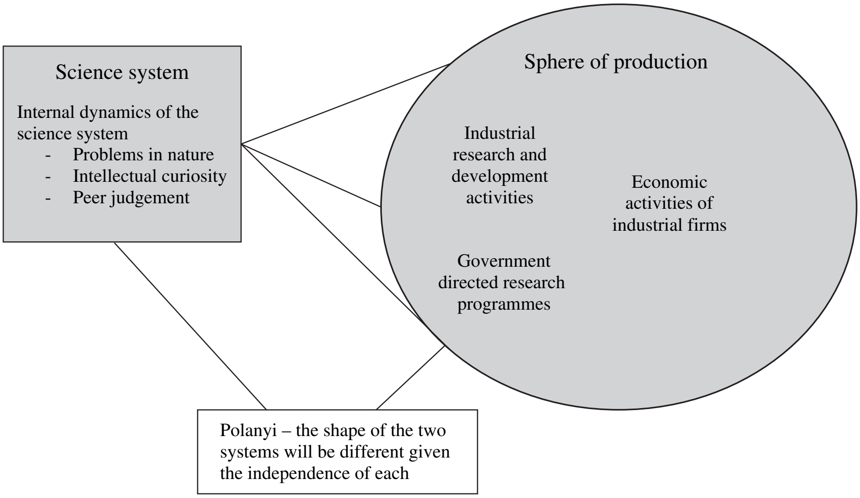

Fig. 2. *Independence of the science system from production – the Polanyi perspective.*

OECD countries have attempted to balance 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. 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, fuelled by the (by then) modern economic analysis of basic research, which demonstrated (Nelson, 1959) that, given problems of non-appropriability of the results from basic research, socially undesirable under-investment would occur, if public funding was not provided.[1] A considerable portion of science funding was linked to targeted programmes or goals, especially in the military and health-related areas. As Keith Pavitt commented (see, for instance, Pavitt, 2000), the biggest two motivations for supporting science in the post-war era were the public's fear of cancer and communism (Irvine and Martin, 1984; Stokes, 1997). It should be pointed out that such rationales for investing in public research (to some extent) make the relationship between the scientific and economic activities less clear. Apart from the targeted research, at the same time substantial funding was provided to the science system to be independently allocated. Among research councils and agencies responsible for the public support of research, however, 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

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[1] More recent econometric studies have found support for this analysis, since they suggest that the economic benefits of publicly funded research are substantial (Salter and Martin, 2001).

often used Bernalian approaches to guide and shape the scientific inquiry, such as Technology Foresight.[1]

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 to the rise of the knowledge-driven economy, arguing that 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 (public) science decision-making should no longer be taken as a given.[2]

3. Empirical background

This shifting policy environment reflects ongoing 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 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, p. 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 systems mutually reinforce each other over time (Nelson, 1994). For example, strength in a particular industry might lead a government to invest in a research programme associated with that industry. Nelson described the general process of institutional development and adaptation as innovation systems' respond to opportunities opening up both in science and industrial practice. Nelson argued 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.

While the previous discussion has been concerned mainly with the more general link between the economic and the scientific spheres, empirical research has identified considerable differences across industries in the importance of science for innovation. Moreover, historical studies have falsified the linear model of science and innovation, stating that technological innovation always emerges out of scientific discovery (Kline and Rosenberg, 1986). Sometimes science has indeed

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[1] Freeman argues that in historical debate between Polanyi and Bernal about the nature of science, the Polanyist position lost the argument (Freeman, 1999). For instance, the Polanyist model 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 (Freeman, 1999, pp. 118–19).

[2] There is an open debate within the science policy community about Gibbons *et al.* approach (see David, 1996).

led to innovation, while in other cases innovation has led to scientific discovery, while in yet other cases, the link between science and innovation has been virtually non-existent. 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 industries and by the high number of academic citations in industrial patents (Hicks *et al.*, 2001). Yet, in other industries, such as car manufacturing and aerospace, the links are much more varied (Klevorick *et al.*, 1995). Moreover, the direct use of scientific knowledge in science-based industries has also been well documented in quite a few case studies. Grupp (1998, p. 361), for instance, documents via patent documents, how inventors in laser medicine very often publish in scientific journals—up to 60% of inventors listed on patent documents from laser medicine publish in scientific journals.

In non-science-based industries, the link between research and innovation is 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 industries.

In order to understand the contribution of different fields of science to innovation better, Klevorick *et al.* break 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, car manufacturers use traditional engineering disciplines, such as mechanical engineering and more basic sciences, such as physics and mathematics (for a similar European study, see 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. The Yale study shows 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.* (1995) do not provide a detailed picture of the links between individual industries 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 fewer (Klevorick *et al.*, 1995). In our approach, we attempt to complement these survey-based approaches using aggregated industrial statistics and more detailed data on scientific publications.

In a large part of the empirical literature on the link between science and innovation, the link is believed to be strong at the national level. In other words, many studies have adopted a ‘national systems of innovation’ view (Lundvall, 1992; Nelson, 1993) of the link between science and innovation. In our study, we follow the same assumption—firms are believed to draw in a disproportional fashion on national science. Considerable support can be found for this assumption, since empirical research has shown that links between academic research and application are inversely related to distance and directly related to common nationality (Jaffe, 1989; Hicks *et al.*, 1994; Narin *et al.*, 1997). In addition, when firms draw on international science, they often do it through national science, which acts as a necessary condition for ‘absorptive capacity’ (Cohen and Levinthal, 1989). Moreover, given that national governments control the majority of public expenditure, it is assumed that more public funds are allocated to scientists active in fields of science relevant to those industries in which the country is specialised. Given those assumptions, we expect to detect a link at the national level between scientific specialisation (and performance), on the one hand, and economic specialisation, on the other, when we conduct our panel data estimation in Section 5 below.

To summarise our discussion on the relationship between the economic and the scientific spheres across nations, we can derive a ‘strong’ Marx–Bernal-inspired hypothesis, stating that (i) relevant (to each industry) scientific specialisation is expected to co-evolve with economic (production) specialisation. Moreover, we (ii) conjecture 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 (this is a ‘weaker’ Marx–Bernal inspired hypothesis—could also be termed ‘the Pavitt-hypothesis’). Since the relationship between the two spheres is much more indirect, when dealing with non-science-based industries, we (iii) 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 many of the non-science-based industries. Finally, we (iv) expect firms in manufacturing industries to draw on a variety of scientific disciplines.

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 1981–94, we conjecture the relevance of 77 scientific fields for 17 manufacturing industries. This procedure hinges on the assumption that, if firms in particular industries publish papers in particular fields of science, they—at least partly—do it because they have, and wish to maintain, an ‘absorptive capacity’ in the relevant scientific fields. In other words, we assume that firms from an industry that publishes in some fields will make use of knowledge developed within the same fields. The ISI database contains publication data for 105 fields of science for 176 countries over the period 1981–98. 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 incomplete after 1994, we use data from all sources over the period 1981–94. 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. The STAN database provides data for the manufacturing industries only, and therefore our analysis excludes service industries. This is a limitation of the present study that should be acknowledged since, although the benefits of scientific activities may in general have a more direct effect on manufacturing activities, some fields of science (such as medical scientific activities) may have very important benefits for service industries (such as medical services).

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 industry, 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. Table 1 only refers to the scientific production of industrial firms and not the use these firms make of public knowledge. For this analysis, we used 292 firms, each of which had at least ten scientific publications. We then divided these firms into 17 industries (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 industry 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 industry and the numbers of firms included in the analysis. Owing 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.

Table 1. *Spread of industrial scientific publications by private firms across scientific disciplines in the UK by industrial sector: total sum of publications in the sample over the period 1981–94*

	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 & plastics	38	0.112	251	5
Food, drink & tobacco	52	0.116	880	9
Aerospace	44	0.117	462	9
Pharmaceuticals	73	0.119	12478	46
Office machines & computers	39	0.132	315	9
Motor vehicles	19	0.150	41	2
Instruments	45	0.187	394	6
Stone, clay & glass	65	0.199	3629	20
Iron & steel	20	0.249	165	1
Non-ferrous metals	21	0.254	118	2
Communication eq. & semiconductors	35	0.315	2354	6
Electrical machinery	40	0.405	2559	12

Notes: 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.

Table 1 demonstrates that each industry is highly multidisciplinary; that is, it is active in a wide number of different scientific fields. Industrial chemicals appear to be the most active industry, with the broadest number of publications across the scientific fields (75). Industrial chemicals are followed by Pharmaceuticals (73) and Stone, clay & glass (65). Motor vehicles appear 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 is 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 industries with a limited number of scientific publications, yet they remain relatively broadly spread across a range of fields, such as

Non-electrical machinery.[1] This suggests that, even in industries 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.

4.2 The empirical model

In order to examine the link between national scientific activities and economic specialisation, we set up a model of the determinants of economic specialisation:

$$IS = f(\beta_1 x, \beta_2 z) \tag{1}$$

where *IS* is international economic specialisation, while β_1 and β_2 are parameter vectors. *x* represents variables measuring national scientific activities, while *z* is a set of control variables. Below we explain how we make this model operational.

4.2.1 The dependent variable

The left-hand side variable in our econometric analysis is the measure of economic specialisation (*IS*) which has been chosen to take the form of the revealed production advantage (cf., Balassa, 1965). The algebra can be set up as follows:

$$RPA_{ijt} = \frac{\left(Y_{ijt} / \sum_i Y_{ijt} \right)}{\left(\sum_j Y_{ijt} / \sum_i \sum_j Y_{ijt} \right)} \tag{2}$$

where the numerator represents the percentage share of a given industry in national manufacturing; Y_{ijt} is production of industry *i* from country *j* at time *t*. The denominator represents the percentage share of a given industry 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 industry in a given country, the percentage share of that industry is identical with the OECD17 average. When *RPA* is above 1, the country in question is said to be specialised in that industry 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 symmetrical, obtained as

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[1] 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.

($RPA-1$)/($RPA+1$); this measure ranges from -1 to $+1$. The measure is labelled 'revealed symmetric production advantage' (*RSPA*).[1]

4.2.2 The independent variables measuring science

We include two measures of scientific activity relevant to our 17 manufacturing industries: one variable measures the scientific strength (or performance), and another variable measures scientific specialisation. These variables are central to our analysis. However, first we adjust for the unequal size of scientific disciplines by weighing the concordance table 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 vector obtained by the total population of the given country. Next, the resulting vector is multiplied (element-wise) by the adjusted concordance matrix (77 fields of science × 17 industries). The variable is then subsequently calculated by adding up the 77 fields for each of the 17 industries. In this way we get a single figure measuring the 'relevant' scientific strength for each industry (labelled *SP*, i.e., short for 'scientific performance'). The procedure is repeated for all years (14 years; 1981–94) and countries (17 countries). The ISI database contains national publications from all publishing entities such as educational, medical, industrial and governmental institutions. We have strong indications that the bulk of the publications are the result of publicly funded research. For example, in the UK about 95% of all published papers in 1994 had an author or a co-author with an educational, medical or governmental affiliation (Hicks and Katz, 1996). About 8% of the papers had an author or a co-author with an industrial affiliation.

The variable measuring specialisation relevant to each of the 17 industries is obtained by calculating a 'comparative advantage figure' (analogous to equation1) based on the ISI data (for an analysis of scientific specialisation across countries *per se*, see Pianta and Archibugi, 1991). Subsequently, the obtained vector of specialisation is multiplied (element-wise) by the adjusted concordance matrix (77 fields of science × 17 industries). As in the case of scientific performance, the variable is then subsequently calculated by adding up the 77 fields for each of the 17 industries. However, since by following this procedure, we are likely to get countries 'specialised' in all 17 industries, we normalise the result by calculating yet another comparative advantage figure, across the 17 industries. Using this approach, we obtain the 'revealed symmetric scientific advantage' (*RSSA*). The procedure is the repeated for all years and countries.

4.2.3 Control variables

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

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[1] For a discussion of this topic, see Laursen (2000).

conducting an analysis of the relationship between national scientific specialisation and strength on the one hand, and economic specialisation on the other, 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:

$$ULC_{ijt} = \frac{(W_{ijt}/VA_{ijt})}{\sum_{j}[(W_{ijt}/VA_{ijt})/n]} \tag{3}$$

where W_{ijt} is the wage sum of country j, in industry i, at time t, expressed in current prices and VA_{ijt} is value added in fixed prices; n is the number of countries.[1] 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 industry.

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 is therefore defined in a similar way to the *RSPA* from above, but in this case the input to equation (2) is not production, but instead US patents by industry, country and time. In this case, we obtain the 'revealed symmetric technological advantage' (*RSTA*).

Moreover, since we include a measure of scientific strength (based on a measure of publications shares), technological strength (patent shares) should be controlled for as well. The variable can be defined as follows:

$$PATS_{ij} = \frac{\left[P_{ij} \Big/ \left(\sum_{j} P_{ij}\right)\right]}{POP_j} \tag{4}$$

where P_{ij} is the number of patents in industry i from country j. POP_j is the population size of the country in question. Hence, the variable measures a country's share of patents within a given industry, normalised for country size. 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 (for both *RSTA* and *PATS*).

5. Econometric analysis

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

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[1] Note that our sample includes four-digit ISIC industries for which no constant price value added is available (Pharmaceuticals, Computers & office machines, Electronics, Other transport, Aerospace). For these industries, we use the corresponding three-digit (implicit) price indices for calculating constant price value added.

$$RSPA_{ijt} = \beta_{1i} + \beta_{2j} + \beta_{3i}RSTA_{ijt} + \beta_{4i}PATS_{ijt} + \beta_{5i}ULC_{ijt} + \beta_{6i}SP_{ijt} + \beta_{7i}RSSA_{ijt} + \varepsilon_{ijt} \tag{5}$$

where β_{1i} is an industry-specific effect, β_{2j} is a country-specific effect, and ε_{ijt} is the error term. *RSPA* is our measure of production specialisation, *RSTA* is the measure of technological specialisation, *PATS* is the measure of technological strength *per capita*, *ULC* is unit labour costs, *SP* is the measure of scientific strength relevant to the industry scientific fields *per capita*, while *RSSA* measures relevant to the industry scientific specialisation. Subsript *i* on the parameters indicates that the model is to be estimated while allowing the slopes to differ in the industry 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 relatively 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. The model is estimated for a panel of 14 years (1981–94) and 17 countries.

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 industry. 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, p. 200).

The results of the estimation of equation (5) are displayed in Table 2. From Table 2, it can be seen that technology (both measured as specialisation -*RSTA*- and as strength -*PATS*) is an important factor in explaining specialisation in terms of production, since the parameter for these variables are significant in the majority of the 17 industries. The *RSTA* is significant in 11 industries and *PATS* is significant in 13 industries. Overall, technology plays a role in 14 industries. Hence, it can be concluded that technology plays an important role for economic specialisation, not only in high-tech industries, but also in medium-tech and in some low-tech industries.

Unit labour costs also play an important role in determining production specialisation, since eight parameters turn out to be significant at the 10% level (using a two-tailed test). Nine of the 17 coefficients are negative, and six of these coefficients are significant (Industrial chemicals; Pharmaceuticals; Rubber & plastic products; Iron & 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 industry. Apart from Pharmaceuticals, it can be noted that the six negative and significant industries are medium-tech to low-tech industries—industries normally thought to be cost-sensitive areas of production. Nevertheless, two coefficients are positive and significant (Food, beverage & tobacco; Electrical machinery). 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.

For what concerns the science variables, key to the analysis, it can be seen from Table 2 that the results are somewhat mixed. The ‘strong’ version of the Marx–Bernal inspired hypothesis states that economic (*RSPA*) and scientific specialisation (*RSSA*) should be tightly linked. We find support for this in six out of 17 industries. Yet we find

Table 2. *Regression results explaining specialisation in manufacturing production over the years 1981–94, across 17 OECD countries. Unbalanced panel (n=3628)*

	RSTA	*p*-value	*PATS*	*p*-value	*ULC*	*p*-value	*SP*	*p*-value	*RSSA*	*p*-value
Food, beverage & tobacco	−0.04	0.213	0.23	0.168	0.15	0.007	−0.09	0.051	0.55	0.001
Industrial chemicals	0.19	0.000	1.05	0.000	−0.09	0.002	0.12	0.002	0.38	0.001
Pharmaceuticals	0.13	0.000	1.37	0.000	−0.16	0.000	0.06	0.135	−0.29	0.034
Petroleum refineries	0.14	0.000	0.49	0.000	−0.01	0.295	0.02	0.683	0.07	0.818
Rubber & plastic products	0.17	0.000	1.81	0.000	−0.15	0.000	0.03	0.478	0.70	0.000
Stone, clay & glass	−0.02	0.419	0.95	0.562	−0.07	0.060	−0.21	0.000	−0.06	0.741
Iron and steel	0.04	0.323	1.29	0.000	−0.24	0.000	−0.01	0.826	0.56	0.001
Non-ferrous metals	0.32	0.000	1.50	0.000	−0.19	0.000	0.00	0.953	0.22	0.404
Fabricated metal products	0.03	0.346	0.86	0.000	0.02	0.699	0.13	0.001	0.27	0.235
Non-electrical machinery	0.33	0.027	2.19	0.000	0.05	0.583	0.09	0.191	−0.89	0.002
Office & computing machinery	0.29	0.000	2.14	0.000	−0.06	0.199	0.32	0.000	−1.83	0.000
Electrical machinery	0.13	0.003	1.49	0.000	0.29	0.000	−0.26	0.000	0.33	0.101
Communication eq. & semiconductors	0.19	0.018	2.79	0.000	0.00	0.969	0.05	0.253	−0.83	0.000
Other transport equipment	0.00	0.974	0.19	0.358	−0.34	0.000	0.28	0.000	−2.57	0.000
Motor vehicles	0.67	0.000	1.71	0.000	0.19	0.054	0.25	0.000	−0.21	0.530
Aerospace	0.24	0.006	−0.41	0.370	0.06	0.623	0.51	0.000	3.07	0.001
Instruments	0.00	0.962	4.01	0.000	0.04	0.457	0.40	0.000	1.42	0.000

Notes: 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. *RSPA* is revealed symmetric production advantage (measuring economic specialisation), *RSTA* is the revealed symmetric technological advantage (measuring technological specialisation), *PATS* is the given country's share of patents within an industry normalised for population size (measuring technological strength). *ULC* is unit labour costs, *SP* is scientific performance in 'relevant' scientific disciplines, and *RSSA* is revealed symmetric scientific advantage (measuring scientific specialisation in 'relevant' scientific disciplines).

five industries in which scientific and economic specialisation are significantly and negatively related.

The weaker version of the Marx–Bernal-inspired hypothesis, the so-called Pavitt hypothesis, states that science-based industries need a strong national science base in order to be specialised and competitive in international markets. We find considerably more support for this hypothesis, since the coefficients for scientific strength (*SP*) are positive and significant in seven out of 17 cases (Industrial chemicals; Fabricated metal products; Office & computing machinery; Other transport equipment; Motor vehicles; Aerospace; Instruments). Hence, these results show—in general and as expected—that most industries with strong science-based properties[1] (Industrial chemicals; Office & computing machinery; Aerospace; Instruments) rely on the

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[1] 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).

availability of relevant scientific strength (scientific output at a world-class level) held by the given country. Out of the total of six science-based industries, two industries, Pharmaceuticals and Communication equipment & semiconductors, are insignificant although, in both cases, the associated parameters have the expected signs.[1] Three scale-intensive industries also appear to need relevant scientific strength (Fabricated metal products; Other transport equipment; Motor vehicles).

The six industries that rely on scientific specialisation (rather than on performance) are a mixture of science-based and non-science-based industries (three of each). When comparing the results for scientific specialisation and scientific performance, it can be seen that what matters for science-based industries is most often not whether science relevant to a given industry in a country is relatively strong compared with the strength of science relevant to other industries within that country (measured by *RSSA*). Rather, it is important to have absolutely strong science *vis-à-vis* other countries within the same industry (measured by *SP*). Moreover, it can be noted that when comparing the two science variables, the parameters for each variable have opposite signs in eight industries (three of them are significant for both variables). With respect to science-based industries, we can speculate that countries with a weak science base make investments in the scientific disciplines most relevant to science-based industries—such investments would give rise to high values of *RSSA*, but not to high values of *SP*. Such investments do not, however, directly translate into economic specialisation in the science-based industries, because an internationally strong science base is generally what is important for being specialised in these industries.

6. Conclusions

Using a variety of data sources, this paper has explored the relationship between scientific activity and economic specialisation. We have found that the evidence on the link between scientific economic specialisation is mixed. A ‘strong’ Bernal–Marx inspired hypothesis states that economic and scientific specialisation should be positively related in the majority of industries. We found this relationship for just over a third of the industries, but we also found a negative relation for just under a third of the cases.

The weaker version of a Bernal–Marx inspired hypothesis—the so-called Pavitt hypothesis—stating that scientific strength is a necessary condition for being specialised in science-based industries, found more support, since economic specialisation in most of the science-based industries appears to be correlated with relevant (to the industry) scientific strength *per capita*. Moreover, we also detected a possible reliance of many industries upon national scientific strength in some scale-intensive industries. In total, in about 40% of cases, we detected a positive and significant association between national, relevant to the industry scientific strength *per capita* and national economic specialisation. In this sense, the research provides evidence for the dialectical or co-evolution view of the relationship between science and production. Our findings further strengthen the view

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[1] It can be noted that, if patent shares (*PATS*) are not included in the analysis, the parameter for pharmaceuticals becomes significant at the 1% level.

that the science system is often 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. However, it should be underscored that Marx's victory over Polanyi is not definitive—we have certainly not demonstrated the absence of Polanyian blue-sky science in the public domain.

We take the statistically significant association between relevant scientific *strength* and economic specialisation, for most science-based and for some scale-intensive industries, as an indication of a rather direct link to the underlying science-base for what concerns these industries. In addition, the significant and positive relationship between relevant scientific *specialisation* and economic specialisation for some scale-intensive industries is taken as an indication of a much more indirect link to the scientific system. In sum, we found strong support for hypothesis (ii) of this paper, regarding the role of scientific strength and some support for hypothesis (iii) regarding scientific specialisation. Our findings suggest that countries and their governments cannot rely solely on a global pool of scientific knowledge if they want to be specialised in science-based industries. Accordingly, countries need to develop their own scientific basis if they want to take up opportunities in these industries, also because such a national scientific basis is required to absorb scientific knowledge developed elsewhere.

Our analysis also showed that hypothesis (iv) in Section 3 found considerable backing: industries draw from a wide variety of scientific disciplines. In the light of this finding, we suggest that policies aiming to support particular industries by making investments in a narrow range of disciplines commonly associated with those industries will yield only limited results. A broad approach involving 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 only from 1981 to 1994, and the production specialisation indicator is a partial reflection of the production sphere. It goes without saying that it is not easy to measure quantitatively the linkages associated with intellectual (mainly publicly funded) activities of scientists and engineers to the social forces of production. Moreover, the analysis is based solely on data from the manufacturing sector and, given the importance of the service sector in most advanced OECD countries, this is a severe limitation of the analysis. 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 whether 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.

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Appendix

List of countries in the sample

Austria
Belgium
Canada
Denmark
Finland
France
Germany
Greece
Italy
Japan
Netherlands
Norway
Portugal
Spain
Sweden
UK
US