Sectoral patterns of technical change: Towards a taxonomy and a theory

Keith PAVITT *

Science Policy Research Unit, University of Sussex, Brighton BN1 9RF, UK

Final version received January 1984

The purpose of the paper is to describe and explain sectoral patterns of technical change as revealed by data on about 2000 significant innovations in Britain since 1945. Most technological knowledge turns out not to be "information" that is generally applicable and easily reproducible, but specific to firms and applications, cumulative in development and varied amongst sectors in source and direction. Innovating firms principally in electronics and chemicals, are relatively big, and they develop innovations over a wide range of specific product groups within their principal sector, but relatively few outside. Firms principally in mechanical and instrument engineering are relatively small and specialised, and they exist in symbiosis with large firms, in scale intensive sectors like metal manufacture and vehicles, who make a significant contribution to their own process technology. In textile firms, on the other hand, most process innovations come from suppliers.

These characteristics and variations can be classified in a three part taxonomy based on firms: (1) supplier dominated; (2) production intensive; (3) science based. They can be explained by sources of technology, requirements of users, and possibilities for appropriation. This explanation has implications for our understanding of the sources and directions of technical change, firms' diversification behaviour, the dynamic relationship between technology and industrial structure, and the formation of technological skills and advantages at the level of the firm, the region and the country.

* The following paper draws heavily on the SPRU data bank on British innovations, described in J. Townsend, F. Henwood, G. Thomas, K. Pavitt and S. Wyatt, *Innovations in Britain Since 1945*, SPRU Occasional Paper Series No. 16, 1981. The author is indebted to Graham Thomas and to Sally Wyatt who helped with the statistical work, to numerous colleagues inside and outside SPRU for their comments and criticisms, and to Richard Levin and two anonymous referees for their detailed and helpful comments on a longer and more rambling earlier draft. The research has been financed by the Leverhulme Trust, as part of the SPRU programme on innovation and competitiveness.

Research Policy 13 (1984) 343–373
North-Holland

1. Introduction

1.1. Purpose

The subject matter of this paper is sectoral patterns of technical change. We shall describe and try to explain similarities and differences amongst sectors in the sources, nature and impact of innovations, defined by the sources of knowledge inputs, by the size and principal lines of activity of innovating firms, and by the sectors of innovations' production and main use.

It is recognised by a wide range of scholars that the production, adoption and spread of technical innovations are essential factors in economic development and social change, and that technical innovation is a distinguishing feature of the products and industries where high wage countries compete successfully on world markets [55]. However, representations of the processes of technical change found in economics are in many respects unsatisfactory. According to Nelson:

> In the original neo-classical formulation, new technology instantly diffuses across total capital. In the later vintage formulation, technology is associated with the capital that embodies it and thus adoption of a new technique is limited by the rate of investment. [29]

Whilst such assumptions may be convenient or useful in macro-economic model building and analysis, they have – as Nelson [29] and Rosenberg [42] have pointed out – two important limitations. First, they make exogenous the production of technology and innovations. Second, they do not reflect the considerable variety in the sources, nature and uses of innovations that is revealed by empirical studies and through practical experience.

Such formulations of technical change are not therefore very useful for analysts or policy makers concerned with either the nature and impact of technical change at the level of the firm or the sector, or with R&D policy at the level of the firm, the sector or the nation. Hence, the importance, we would argue, of building systematically a body of knowledge – both data and theory – that both encompasses the production of technology, and reflects sectoral diversity. The following paper is a contribution to this objective.

1.2. The data base

What makes is possible is data collected by Townsend et al. [60] on the characteristics of about 2000 significant innovations, and of innovating firms, in Britain from 1945 to 1979. The methodology, results and limitations are spelt out fully in the original publication. Suffice here to say that:

(1) Innovation is defined as a new or better product or production process successfully commercialised or used in the United Kingdom, whether first developed in the UK or in any other country.

(2) Significant innovations were identified by experts knowledgeable about, but independent from, the innovating firms; information about the characteristics of the innovations was collected directly from the innovating firms.

(3) The sample of innovations covers three and four digit product groups accounting for more than half the output of British manufacturing. At the two digit level, the sectoral distribution of innovations is similar to that measured by numbers of patents, but is not to that measured by expenditures on R&D activity. In concrete terms, this reflects a slight over-representation of innovations in mechanical engineering and metals; a considerable over-representation in instruments and textiles; a slight under-representation in chemicals and electronics; and a considerable under-representation in aerospace. [1]

(4) Experts in different sectors defined the threshold of significance at different levels, which means that our sample of innovations cannot be used to compare the volume of innovations amongst sectors. However, it can be used to compare patterns of innovative activity within sectors, where the results are consistent with other independent sources of data on innovative activities in the UK and elsewhere (see [36]).

(5) The data measure significant innovations introduced into the UK. They do not measure significant world innovations, nor do they capture the incremental and social innovations that often accompany significant technical innovations. We shall assume that the data on significant innovations are the visible manifestations of deeper processes, involving incremental and social, as well as significant, innovations. We shall also assume that, although the pattern of innovative activities in the UK does have some distinctive features [2], what we are measuring on the whole reflects patterns in most industrial countries, rather than the specific characteristics of the UK.

1.3. Approach and structure

Given the nature of the problem as posed in subsection 1.1, and of the large data base as described in subsection 1.2, the reader might legitimately expect a paper that is largely econometric in nature: an alternative model of technical change to neoclassical ones would be proposed and formalised, and a series of statistical tests would be carried out, that discriminate between the explanatory powers of the competing models. However, this will not be the approach followed, for reasons that go beyond the intellectual propensities and professional limitations of this particular author. Although the statistical data are more comprehensive and systematic than any others previously assembled on innovations, the sample still has a number of limitations. As we have seen, it covers just one half of manufacturing, so important gaps remain. For purposes of statistical analysis, it can be grouped into 11 sectoral categories at the two digit level, and into 26 categories at the three and four digit level. Statistical data on other sectoral properties often cannot be conveniently assembled into the same categories and for the same time periods. We were therefore faced with a choice between "creating" data to make any regressions econometrically more convincing, or making for-

[1] For the number of innovations produced in each two digit sector, see table 2, column 3. For the three to four digit sectors included in the sample, see table 1.

[2] See, for example [34;35].

mal statistical analysis a minor part of the paper. We chose the latter approach, although tentative econometric analysis is described in the Appendix to this paper, and discussed in section 4.

This approach has the advantage of allowing the patterns of the statistical data to be compared to the mind's eye with the rich range of sectoral and firm studies of technical change that have accumulated over the past 25 years. Given that no obvious model of sectoral patterns of technical change emerges from previous theoretical writings, such direct and visual comparisons turned out to be particularly useful.

We present and discuss the main features of the data in section 2, and compare them with some prevailing theoretical assumptions. In section 3, we suggest a taxonomy of sectoral patterns of innovative activity, and a theoretical explanation, that are consistent with the data. In section 4, we explore some of the analytical implications of such a theory, and in section 5 we suggest further research that should be done.

2. Sectoral patterns of innovation

2.1. *Analysis of the data*

The information contained in the data bank describes characteristics of significant innovations and of innovating firms. In this paper, we shall be using information on the institutional sources of the main knowledge inputs into the innovations, on the sectors of production and of use of the innovations, and on the size and the principal sectors (or product groups or lines) of activity of the innovating firms.

Sources of the main knowledge inputs into the innovations were identified by asking the sectoral experts and the innovating firms to identify the type of institution that provided up to the three most important knowledge inputs into each innovation. This information provides a basis for assessing the relative importance in providing such knowledge, of the innovating firms themselves, of other industrial firms, and of institutions providing public knowledge, such as universities and government laboratories. This is done in subsection 2.2.

Information on the sectors of production of innovations comes from the sectoral experts, and on sectors of use from the innovating firms [3]. We define innovations that are used in the same sectors as those in which they are produced (e.g. direction reduction of steel) as *process* innovations, and those that are used in different sectors (e.g. the Sulzer Loom) as *product* innovations. Such information provides what can be considered as the technological equivalent of an input/output table. It shows how intersectoral patterns of production and sale of goods is reflected in intersectoral transfers of technology. It is strictly equivalent in purpose, if not in method, to the table compiled recently for the USA by Scherer [51]. It is discussed in subsection 2.3.

Information on the size and principal sector of activity of innovating firms was provided by the firms themselves, and sometimes checked through other sources. Size is measured in terms of total world employment, and (for the innovations in the period from 1969 to 1979) also of employment in the UK. Such information allows comparisons of the size distribution of innovating firms amongst sectors, over time, and in comparison to other indices of economic activity.

Information on the principal activity of innovating firms allows comparisons, amongst sectors and over time, of the degree to which firms produce innovations outside their principal sector of activity, and to which innovations in sectors are produced by firms with their principal activity elsewhere. Such comparisons can be seen as the equivalent for technology of comparisons of firms' diversification in output, employment or sales. Patterns of size and of "technological diversification" of innovating firms are analysed in subsection 2.4.

It is to be noted that each innovation in the data base is attributed three numbers in the Standard Industrial Classification, or Minimum List Heading, as it is called in the UK: (1) the sector of production of the innovation; (2) the sector of use of the innovation; (3) the sector of the innovating firm's principal activity. We are therefore able to construct an (as yet incomplete) three-dimensional matrix encompassing links amongst sectors in the production and use of innovations, and in the sectoral patterns of "technological diversification" of innovating firms. Such a construct enables us to

[3] When an innovation found a use in more than one sector, we defined the main user sector as the sector of use.

compare sectors in terms of:

(1) The sectoral *sources* of technology *used* in a sector: in particular, the degree to which it is generated within the sector, or comes from outside through the purchase of production equipment and materials.

(2) The institutional *sources* and *nature* of the technology *produced* in a sector: in particular, the relative importance of intramural and extramural knowledge sources, and of product and process innovations.

(3) The *characteristics* of *innovating firms*: in particular, their size and principal activity.

Such comparisons have been made systematically by the author, at the two and the three to four digit level, in the preparation of this paper. They were essential for an evaluation of the empirical validity of prevailing models of technical change, and *a fortiori* for working out the sectoral taxonomy and theory proposed in section 3. However, they will not be reproduced in comprehensive detail since they are long, tedious and sometimes potentially confusing. We shall instead present statistical material mainly at the two digit sectoral level, although we shall also refer to some patterns at the three to four digit level.

Suffice to say here that a central feature in our search for a taxonomy and an explanatory theory was the classification of innovations in each sector according to whether or not the sectors of production, of use, and the principal activity of the innovating firm, are the same. There are five possible combinations:

Category 1: sectors of production, use, and principal firm activity are all the same: e.g. a process innovation by a steel making firm. (MLH [4] 311)

Category 2: sectors of production and principal firm activity are the same, but different from sector of use: e.g. a specialised firm making textile machines (MLH 335), designing a new textile machine (MLH 335) for use in the textile industry (MLH 411).

Category 3: sectors of principal firm activity and of use of the innovation are the same, but different from the sector of production of the innovation: e.g. a shipbuilding firm (MLH 370) develops a special machine tool (MLH 332), for use in building ships (MLH 370).

Category 4: sectors of production and use of the innovation are the same, but different from that of the firm's principal activity: for example, a firm principally in general chemicals (MLH 271) develops a process innovation in textiles (MLH 411).

Category 5: sectors of production of the innovation, of its use, and of the firm's principal activity are all different: for example, a firm principally in electronic capital goods (MLH 367) develops and produces an innovation in instrumentation (MLH 354.2) for use in making motor vehicles (MLH 381).

In the particular examples given above, the categories are the same at the two digit as at the three to four digit level. But in some cases they are not. For example, a firm in general chemicals (MLH 271), producing an innovation in pharmaceuticals (MLH 272), for use in medical services (MLH 876) will fall into category 5 at the three digit level, and category 2 at the two digit level.

2.2. Institutional sources of main knowledge inputs

As we have already pointed out, experts could allocate up to three institutional sources of knowledge inputs for each innovation. All provided one such source, about 40 percent provided two sources, but only 3 percent provided three sources.

The results at the three to four digit level are summarised in table 1. Only about 7 percent of the knowledge inputs comes from the public technological infrastructure (higher education, government laboratories, and research associations). The highest proportion is reached in a number of electronics sectors, but even here it is never as much as 25 percent. On the other hand, 59 percent came from within the innovating firms themselves, and about a third from other industrial firms.

These data have a number of imperfections. Given that they were collected mainly from industrial experts, and that only about 1.5 sources were identified for each innovation, they underestimate the contribution made by the public technological infrastructure to person-embodied knowledge and to essential background knowledge for the innovations. [5] More generally, the distribu-

[4] MLH = Minimum List Heading.

[5] See Gibbons and Johnston [14] for an excellent analysis of these sources.

Table 1
Distribution of knowledge inputs into significant innovations, according to institutional source

Sector [a]	Source of knowledge inputs (%) [b]			Number of observations
	Intra-firm	Other firm	Public Infrastructure	
Food (211-229)	53.4	44.6	2.0	101
Pharmaceuticals (272)	62.8	37.2	0	129
Soap and detergents (275)	60.0	40.0	0	30
Plastics (276)	40.4	55.2	4.4	114
Dyestuffs (277)	68.1	30.5	1.4	69
Iron and steel (311)	47.7	44.9	7.4	149
Aluminium (321)	68.0	28.0	4.0	50
Machine tools (332)	64.1	29.8	6.1	231
Textile machinery (335)	61.2	36.6	2.2	278
Coal-mining machinery (339.1)	52.3	31.6	16.1	199
Other machinery (339.4 + 339.9)	59.1	36.6	4.3	115
Industrial plant (341)	51.6	41.9	6.5	31
Instruments (354.2)	61.6	25.2	13.2	440
Electronic components (364)	48.2	37.1	14.7	170
Broadcasting equipment (365)	64.4	33.9	1.7	59
Electronic computers (366)	50.6	33.3	16.1	81
Electronic capital goods (367)	67.2	9.7	23.0	113
Other electrical goods (369)	60.8	35.3	3.9	51
Shipbuilding (370)	47.9	43.8	8.2	73
Tractors (380)	78.7	21.3	0	47
Motor vehicles (381)	69.3	29.7	1.0	101
Textiles (411-429)	67.3	32.7	0	110
Leather goods and footwear (431/450)	44.4	48.1	7.4	54
Glass (463)	48.2	44.6	7.1	56
Cement (464)	62.5	33.3	4.2	24
Paper and board (481)	66.7	28.2	5.1	39
Other plastics (496)	55.8	41.9	2.3	43
Other	–	–	–	56
Total	58.6	34.0	7.4	3013

[a] Numbers in brackets refer to the appropriate Minimum List Heading.
[b] Each row adds up to 100 percent.

tion of knowledge sources in this kind of study depends heavily on the definitions and time perspectives of the data collected. [6] In spite of these imperfections, the distribution of knowledge sources in table 1 is not dissimilar to that found in other studies. [7].

Given that innovating firms evaluate their own knowledge contributions at nearly 60 percent of the total, we cannot realistically assume that there exists a generally available and applicable stock or pool of knowledge, where each firm – being very

[6] See, for example, the classic US controversy at the end of the 1960s: the Hindsight and Traces studies arrived at very different conclusions about the contribution of basic research to industrial innovation. For a comparison, see Pavitt and Wald [39].

[7] See Langrish et al. [21], and Gibbons and Johnston [14].

small in relation to the total stock or pool – can gain much more from drawing on the pool, rather than by adding to it. The concept of the general "pool" or "stock" of knowledge misses an essential feature of industrial technology, namely, the firm-specific and differentiated nature of most of the expenditures producing it. In Britain and elsewhere, about three-quarters of all expenditures on industrial R&D is on "D", and an equivalent sum is spent on testing and manufacturing start up. [8] The purpose of these expenditures is to mobilise skills, knowledge and procedures in the firm in order to commercialise specific products and production processes, with the characteristics of operation, reliability and cost that satisfy user needs. Specificity is an essential feature of innovations and innovative activity in capitalist firms – both in terms of functional applications, and of the ability of the innovating firm to appropriate the relevant knowledge for a period of time.

This feature is missed in any simple equation of "technology" with "information." Whilst it may be reasonable to describe *research* and *invention* as producing "information" that is quickly and easily transmitted, [9] it is grossly misleading to assume that *development* and *innovation* have similar properties. Given their specific characteristics, the costs of transmission from one firm to another can be high, even in the absence of legal protection or secrecy in the innovating firm [7;33;57]. As Nelson [30] has recently argued, technological knowledge has both proprietary and public aspects, although table 1 and other studies suggest that the former outweigh a latter.

These features are missed in some representations of technology in a production function. According to Salter:

> ...the production function concept ... could refer either to techniques which have been developed in detail, or to techniques which are feasible in principle but have not been developed because the necessary economic pressures are absent. [48, p.26]

Salter plumps for the latter and, in doing so, makes exogenous to his analysis most of the innovative (i.e. development and post-development) activities of industrial firms. As Rosenberg [42] has pointed out, most firms do not (and in the light of the above discussion cannot) have information on a full and complete range of alternative techniques. The assumption that most technological knowledge is or could be publicly available and generally applicable has little foundation in reality.

2.3. Sectoral patterns of production and use of innovations

As already described above, the innovation data base compiled by Townsend et al. [60] describes sectoral patterns of production and use of innovations in the UK. On the basis of a different method, Scherer [51] has compiled similar information for the USA. He obtained detailed data on the sectoral allocations of R&D resources in more than 400 large US firms in the 1970s. On the basis of examination of the patenting activity of these firms, he was also able to attribute the "output" of this R&D to sectors of use. Scherer's work covers more than 40 US sectors of production and use. The data collected by Townsend et al., on the other hand, cover small and medium sized, as well as large firms, but not all sectors. Most important for the purposes of this paper, both studies show comparable results in sectoral patterns of production and use of technology. [10]

Following Scherer, we define as product innovations those innovations that are used *outside* their sector of production, and *process* innovations as those that are used *inside* their sector. [11] Both studies confirm the prevalence of *product* innovations which accounted for 73.8 percent in the USA, according to Scherer, and 75.3 percent in the UK, when sectors are defined at the three to four digit level, and 69.6 percent when defined at the two digit level.

[8] For a recent review of empirical findings on the total costs of innovation, see Kamin et al. [19].

[9] See the classic paper by Arrow [3].

[10] See Pavitt [36].

[11] This definition is not strictly the same as product or process innovation at the level of the firm. Thus, what is a product innovation for the firm will be a process innovation for the sector, when the firm's innovation is purchased and used in the same sector; conversely, a process innovation in the firm will be a product innovation for the sector, when the firm produces and uses its capital goods. However, for the firm, as well as the sector, product innovation predominates. See Townsend et al. [60, tables 9.1 and 9.2].

Table 2
Innovations produced and used in two digit sectors

Innovations used in sector		Sector [a]	Innovations produced in sector	
Percentage produced in sector	Number		Number	Percentage that are product innovations
(1)	(2)	(3)	(4)	(5)
52.9	68	III Food and drink	65	44.7
60.5	71	V Chemicals	251	82.9
60.7	130	VI Metal manufacture	137	42.3
68.1	169	VII Mechanical engineering	662	82.7
38.4	60	VIII Instrument engineering	332	93.1
80.8	107	IX Electrical and electronic engineering	339	60.1
32.2	90	X Shipbuilding	52	44.1
37.6	221	XI Vehicles	128	35.2
16.2	377	XIII Textiles	91	32.9
60.0	45	XIV&XV Leather and Footwear	34	26.5
46.1	63	XVI Bricks, Pottery, glass and cement	72	85.0
na	823	Other	61	na
41.9 [b]	2224	Total	2224	69.6

[a] Roman numerals refer to the appropriate Order Headings.
[b] For the 1401 innovations in the sample that are attributed a sector of use.

Scherer's more complete and comprehensive data for the USA show a clear difference in the production and use of innovations between manufacturing and the other sectors of the economy (i.e. agriculture, mining, service industries, private and public services). For manufacturing as a whole, the ratio of production to use of technology is about 5.3 to 1. Outside manufacturing it is about 0.1 to 1, and the proportion of all the technology used outside manufacturing that is generated there amounts to less than 7 percent. In other words, manufacturing produces most of the innovations that get used in other parts of the economy.

However, manufacturing itself is far from homogeneous in patterns of production and use of innovations. Table 2 shows at the two digit level, the relevant characteristics of those sectors of British manufacturing for which we have a satisfactory sample of innovations. Column 5 shows the percentage of all innovations produced in each sector that are purchased and used in other sectors: in other words, the percentage of product innovations. These are relatively most important in instruments, mechanical engineering, chemicals, building materials (mainly glass and cement) and electrical and electronic engineering, whilst process innovations predominate in leather and footwear, textiles, vehicles, metal manufacture, shipbuilding and food and drink. Data at the three to four digit level show that all the mechanical engineering product groups covered in the survey are strongly orientated towards product innovations whilst, within the chemical and the electrical/electronic sectors, there are two product groups with high percentages of process innovations: soaps and detergents, and broadcasting equipment.

Column 1 in table 2 shows the percentage of innovations used in each sector that are produced in the same sector: in other words, the degree to which each sector generates its own process innovations. [12] They show that most two digit sectors of manufacturing in the sample make a significant contribution to developing their own process technologies. The main exception is textiles, which is heavily dependent on innovations from other sectors.

Finally, a comparison between columns 4 and 2 of table 2 shows the differences between production and use of innovations in each sector. Production is greater than use in chemicals, mechanical engineering and instruments, and electrical/electronic products. The two are roughly in balance in industries characterised by continuous process

[12] Column 2 shows 823 innovations produced in the identified sectors of manufacturing but used elsewhere. Unlike Scherer, we cannot in this context usefully allocate these innovations to user sectors, since we do not yet have a sample of innovations produced by these sectors of use.

technology (i.e. food and drink, metal manufacture, building materials), whilst more innovations are used than produced in sectors characterised by assembly operations (i.e. shipbuilding and vehicles). These assembly industries also draw on a wider range of sectors for their process technologies than do those characterised by continuous process technology.

How does this pattern of production and use of innovations compare with the "vintage" model of technical change, which assumes that all technology is capital-embodied and enters the economy through investment? In his original formulation of this model, Salter [48] was very well aware of its limitations. He recognised the importance of innovations in capital goods, and of product innovations, but made them exogenous. He also stated that other assumptions made it "highly simplified" (p. 64): for example, that technical change involves no cumulative effects from one generation of capital equipment to another, or that "best practice" performance is clearly defined and instantly reached.

Nonetheless, Salter's assumptions do reflect the reality of most of the economy, namely non-manufacturing, where technical change comes mainly through the purchase of equipment, materials and components from manufacturing. Within manufacturing, it also reflects accurately the sources of process innovations in the textile industry. However, his characterisation of the sources of technical change at the more modern end of manufacturing industry is less satisfactory, in three respects.

First, whilst it may be conceptually correct in certain economic models to assume – as Salter does – that improvements in the performance of capital goods (i.e. product innovations) are equivalent to the relative cheapening of capital goods (i.e. process innovations), such an assumption is misleading about the directions and sources of technical change in the capital goods sector. Innovative activities are in fact heavily concentrated on product innovation: no amount of process innovation in, for example, the production of mechanical calculators would have made them competitive with the product innovations resulting from the incorporation of the electronic chip.

Second, Salter's model assumes that process innovations come to user sectors already developed. However, we see in table 2 that a significant proportion of the innovations used in modern manufacturing are developed and produced in the innovating sectors themselves. It is worth dwelling a bit on one of the possible reasons why. We know from the research of Gold [15], Sahal [47] and others that two of Salter's simplifying assumptions are false: in continuous process and assembly industries, there is in fact cumulative learning, and "best practice" performance is rarely easily defined or quickly reached. The same design, engineering and operating skills that enable rapid learning are also capable of making innovations, particularly in production equipment. In other words, sectors with complex and expensive process technologies devote considerable technical resources to ensuring that equipment is used efficiently and continuously improved.

Third, and more generally, the production of all innovations is made exogenous to Salter's model. Before suggesting in section 3 a framework that makes such production endogenous, we shall describe characteristics of innovating firms in different sectors.

2.4. Characteristics of innovating firms: Size and technological diversification

Table 3 summarises the main features of the size distribution of innovating firms in different sectors. Columns 7–9 classify them according to the principal sector of activity of the innovating firm. This classification shows a relatively big contribution by small firms (1–999 employees) in mechanical and instrument engineering, textiles, and leather and footwear; and by large firms (10,000 and more employees) in the other sectors. This sectorally differentiated pattern is very similar to that emerging from a study of significant innovations and innovating firms undertaken for the USA. [13]

Columns 1–3 of table 3 show the size distribution of innovating firms according to the sector of the innovations, rather than the principal sector of the innovating firms' activity. In sectors where large firms predominate, the two size distributions are very similar. However, in mechanical and instrument engineering and in textiles, both the number of innovations and the relative contribu-

[13] See [20]. A comparison between the two sets of results is made in [60, table 5.3].

Table 3
Distribution of Innovations by firm size [a] and by sector

By sector of innovation				Sector [b]	By sector of firm activity			
Percentage distribution [c]			Number of innovations		Number of innovations	Percentage distribution [c]		
10,000+	1000–9999	1–999				10,000+	1000–9999	1–999
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
72.3	10.8	17.0	65	III Food and drink	78	79.5	7.7	12.8
74.9	16.8	8.4	251	V Chemicals	290	82.4	7.9	9.6
63.5	31.4	5.1	137	VI Metal manufacture	143	62.9	32.8	4.2
35.2	30.5	34.3	662	VII Mechanical engineering	536	24.3	36.9	38.8
41.0	16.6	42.4	332	VIII Instrument engineering	187	24.6	21.4	54.0
66.4	15.9	17.7	339	IX Electrical and electronic engineering	343	65.9	12.2	22.0
57.7	38.5	3.8	52	X Shipbuilding	89	61.8	34.8	3.3
70.3	18.0	11.7	128	XI Vehicles	158	72.2	20.3	7.6
56.0	30.8	13.2	91	XIII Textiles	77	35.1	40.3	24.7
11.8	20.6	67.6	34	XIV&XV Leather and footwear	50	44.0	18.0	38.0
70.8	18.1	11.1	72	XVI Bricks, pottery, glass and cement	87	74.7	16.1	9.1
–	–	–	112	Other	227	–	–	–
53.2	21.9	24.9	2265	Total	2265	53.2	21.9	24.9

[a] Measured by number of employees.
[b] Roman numerals refer to the appropriate Order Headings.
[c] Rows add up to 100 percent.

tions of large firms are bigger when classified by sector of innovation, than when classified by the principal sector of activity of the innovating firm. In other words, a relatively large number of innovations are produced in these sectors by relatively large firms with their principal activities in other sectors.

Table 4 shows that for the sample as a whole,

Table 4
The distribution of innovations produced outside innovation firms' principal two-digit activities

Innovations in other sectors by firms with principal activities in the sector		Sector [a]	Innovations in the sector by firms with principal activities In other sectors	
%	Number		Number	%
(1)	(2)	(3)	(4)	(5)
30.8	78	III Food and drink	65	17.0
26.5	290	V Chemicals	251	15.2
34.3	143	VI Metal manufacture [b]	137	31.4
(37.0)	(119)		(93)	(19.4)
16.0	536	VII Mechanical engineering	662	32.1
19.8	187	VIII Instrument engineering	332	54.6
23.8	343	IX Electrical and electronic engineering	339	23.0
58.4.	89	X Shipbuilding	52	28.9
33.5	158	XI Vehicles	128	18.0
24.7	77	XIII Textiles	91	36.3
50.0	50	XIV&XV Leather and footwear	34	26.5
32.4	87	XVI Bricks, pottery, glass and cement	72	18.1
–	227	Other	102	–
31.5	2265	Total	2265	31.5

[a] Roman numerals refer to the appropriate Order Headings.
[b] Percentages between brackets refer to Iron and steel only.

31.5 percent of the innovations are produced by firms with their principal activities in other two digit sectors. Column 5 shows that a relatively large proportion of innovations in mechanical and instrument engineering and textiles are produced by firms with their principal activities elsewhere (32.1, 54.6 and 36.3 percent respectively), whilst column 1 shows that firms with their principal activities in mechanical and instrument engineering and in textiles produce a relatively small proportion of innovations in other sectors (16.0, 19.8 and 24.7 percent respectively).

Column 1 also shows the sectors where firms principally in them produce a proportion of innovations in other sectors that is above or round about the average: food and drink, metal manufacture, shipbuilding, vehicles, leather and footwear, and building materials. This is in contrast with firms principally in chemicals, or in electrical and electronic products, neither of which produce relatively high proportions of innovations beyond their two digit sector (26.5 and 23.8 percent respectively). Similarly, a relatively small proportion of innovations in these two sectors are produced by firms principally in other sectors (15.2 and 23.0 percent respectively).

This pattern suggests, amongst other things, that a relatively high proportion of innovations in mechanical and instrument engineering are produced by firms typified by continuous process and assembly production, such as metal manufacture, shipbuilding and vehicles. A more detailed examination of the data base confirms that this is the case. Innovations in two fundamentally important sectors of production technology – mechanical and instrument engineering – are therefore made both in relatively small specialised firms in these sectors, and in relatively large firms in continuous process and assembly industries.

One question springs to mind, when examining the data in tables 3 and 4: to what extent are the intersectoral differences in the size distribution of innovating firms, and in their patterns of technological diversification, similar to those found in the size distribution and patterns of sectoral diversification, in terms of sales, output and employment? Given the gaps in the data in the UK censuses of production, it is not possible to provide a straightforward answer to this question. Certainly, there are similarities: small firms makes a relatively greater contribution to net output and employment in mechanical and instrument engineering than in the other two digit sectors in our sample; and over time, both the increasing contribution to the production of innovations of firms with more than 10,000 employees and the constant share of firms with less than 200 employees, are reflected in trends in both output and employment.

The similarities are at first sight far less apparent in patterns of diversification. A comparison with Hassid's analysis [17], based on data from the UK census of production, shows that diversification at the two digit level is considerably less in net output than it is in the production of innovations: 14.0 percent in 1963 and 16.9 percent in 1968, compared to 31.5 percent for the whole period from 1945 to 1979. Neither is there any close relationship across sectors between the degree to which firms principally in them diversify into other sectors in net output, and in the production of innovations.

However, there is a similarity in the sectors into which firms diversify: a comparison of table 4 above with Hassid's data [17, table 3] shows that, in terms of both the production of innovations and the net output, mechanical and instrument engineering are sectors where relatively large contributions are made by firms principally in other sectors, whilst relatively small contributions are made in food, chemicals, electrical and electronic engineering, and vehicles by such firms.

Taking these comparisons further will need much more time and space, and will not be done in this paper. Our contribution here hopefully will be to enrich the ways in which such comparisons will be interpreted and explained. In particular, we intend to go beyond explanations of sectoral patterns of production of innovations simply in terms of sectoral industrial structures. Even if there turned out to be perfect statistical correlations across sectors between firm size and sectoral patterns of output, on the one hand, and firm size and sectoral patterns of production of innovations, on the other, it would be wrong to interpret the latter simply as causal consequences of the former. This would neglect the causal links running from the latter to the former: that is, from diversification in the production of innovations to diversification in output, and from the production of innovations to firms growth and firm size.

Most of the empirical studies of patterns of diversification do in fact refer to the notion of "technological proximity" in explaining diversification in output [4;16;17;46;62]; our analysis and explanation will try to give some additional empirical and theoretical content to this notion. Similarly, a number of writers have recently stressed the causal links running from innovation to firm size [23,32]; we shall begin to explain, amongst other things, why high rates of innovation do not necessarily lead to heavily concentrated industries. Before doing this, however, we propose in section 3 how and why patterns of technological development and innovation differ amongst sectors.

3. Towards a taxonomy and a theory

3.1. The ingredients

Two central characteristics of innovations and innovating firms emerge from section 2. First, from subsection 2.2 it is clear that most of the knowledge applied by firms in innovations is not general purpose and easily transmitted and reproduced, but appropriate for specific applications and appropriated by specific firms. We are therefore justified in assuming, like Rosenberg [42], that, in making choices about which innovations to develop and produce, industrial firms cannot and do not identify and evaluate all innovation possibilities indifferently, but are constrained in their search by their existing range of knowledge and skills to closely related zones. In other words, technical change is largely a cumulative process specific to firms. What they can realistically try to do technically in future is strongly conditioned by what they have been able to do technically in the past.

The second characteristic is, of cource, variety. From subsections 2.3 and 2.4, it emerges that sectors vary in the relative importance of product and process innovations, in sources of process technology, and in the size and patterns of technological diversification of innovating firms. Nonetheless, some regularities do begin to emerge. In subsection 2.3, we can see a whole class of sectors where – as in vintage models – technical change comes mainly from suppliers of equipment: non-manufacturing and traditional sectors of manufacturing like textiles. We also ssee that the other manufacturing sectors make a significant contribution to their process technology. However, whilst firms in assembly and continuous process industries tend to concentrate relatively more of their innovative resources on process innovations, those in chemicals, electronic and electrical engineering, mechanical engineering, and instrument engineering devote most of these resources to product innovation.

In subsection 2.4, we see that sectors making mainly product innovations can be divided into two categories. First, firms principally in the chemicals and electronic and electrical sectors are relatively big, they diversify relatively little beyond their two digit category in producing innovations, and they produce a relatively high proportion of all the innovations in the two sectors. Second, firms principally in mechanical engineering and instrument engineering are relatively small, they diversify technologically relatively little beyond their two digit category, and they make a smaller contribution to all the innovations in the two sectors, given the important contribution made by relatively large user firms, particularly those in sectors typified by assembly and continuous process production.

In subsections 3.2–3.5 below, we shall try to categorise and explain these characteristics: in other words, to propose a taxonomy and a theory of sectoral patterns of technical change. Ideally, these should be consistent with the data so far presented. They should also be capable of further empirical refinement and test, given the inadequacies of the data at present available, and in particular of using what is mainly static, cross-sectional data as the basis for a theory that is essentially dynamic.

In our proposed taxonomy and theory, the basic unit of analysis is the innovating firm. Since patterns of innovation are cumulative, its technological trajectories will be largely determined by what is has done in the past in other words, by its principal activities. Different principal activities generate different technological trajectories. These can usefully be grouped into the three catogories, that we shall call supplier dominated, production intensive, and science-based. These different trajectories can in turn be explained by sectoral differences in three characteristics: sources of technology, users' needs, and means of appropriating benefits. The three categories, the differing technological trajectories, and their underlying causes are

Table 5
Sectoral technological trajectories: Determinants, directions and measured characteristics

Category of firm	Typical core sectors	Determinants of technological trajectories: Sources of technology	Type of user	Means of appropriation	Technological trajectories	Measured characteristics: Source of process technology	Relative balance between product and process innovation	Relative size of innovating firms	Intensity and direction of technological diversification
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Supplier dominated	Agriculture; housing; private services traditional manufacture	Suppliers Research extension services; big users	Price sensitive	Non-technical (e.g. trademarks, marketing, advertising, aesthetic design)	Cost-cutting	Suppliers	Process	Small	Low vertical
Production intensive: Scale intensive	Bulk materials (steel, glass); assembly (consumer durables & autos)	PE suppliers; R&D	Price sensitive	Process secrecy and know-how; technical lags; patents; dynamic learning economies;	Cost-cutting (product design)	In-house; suppliers	Process	Large	High vertical
Production intensive: Specialised suppliers	Machinery; instruments	Design and development users	Performance sensitive	design know-how; knowledge of users; patents	Product design	In-house; customers	Product	Small	Low concentric
Science based	Electronics/ electrical; chemicals	R&D Public science; PE	Mixed	R&D know-how; patents; process secrecy and know-how; dynamic learning economies	Mixed	In-house; suppliers	Mixed	Large	Low vertical / High concentric

[a] PE = Production Engineering Department.

summarised in table 5. Before discussing them in greater detail, we shall identify briefly the three traditions of analysis on which the taxonomy and the theory are based.

First, there are analysts who have deliberately explored the diversity of patterns of technical change. In particular, Woodward [69] has argued that appropriate organisational forms and mixes of skills for manufacturing firms are a function of their techniques of production, which she divided into three: small batch production and unit production, large batch and mass production, and continuous process production. Our proposal is in the same spirit but, whilst it has some common elements, its focus is different: encompassing product as well as process changes, and linkages with suppliers, customers and other sources of technology. Already in the 18th century, Adam Smith was aware of diversity in the sources of technical change, and of its dynamic nature; as we shall soon see, he identified many elements of our proposed taxonomy in Chapter One of *The Wealth of Nations* [54].

Second, there is the work of Penrose [41] on the nature of firms' diversification activities, and the importance of their technological base. Recent French writings, exploring the notion of *filière*, are in the same tradition [58], as is the work of Ansoff [2] and others on business strategy, and the recent contribution by Teubal [59] on the nature of technological learning.

Third, a number of analysts have explored the cumulative and dynamic nature of technical change: for example, Dosi [8], Freeman et al. [12], Gold [15] Nelson and Winter [31;32], Rosenberg [42;43] and Sahal [47]. From their research has emerged the notion of "technological trajectories," namely, directions of technical development that are cumulative and self-generating, without repeated reference to the economic environment external to the firm.

Nelson has gone further and suggested a framework for explaining technological trajectories [20]. He has argued that it any institutional framework, public or private, market or non-market, technical change requires mechanisms for generating technical alternatives; for screening, testing and evaluating them; and for diffusing them. In the Western market framework, the rate and direction of technical change in any sector depends on three features: first, the sources of technology; second, the nature of users' needs; third, the possibilities for successful innovators to appropriate a sufficient proportion of the benefits of their innovative activities to justify expenditure on them.

For our purposes, there can be a number of possible sources of technology. Inside firms, there are R&D laboratories and production engineering departments. Outside firms, there are suppliers, users, and government financed research and advice. Similarly, users' needs can vary. For standard structural or mechanical materials, price is of major importance one certain performance requirements are met. For machinery and equipment used in modern and interdependent systems of production, performance and reliability will be given a higher premium relative to purchase price. In the consumer sector – as Rosenberg [41] and Gershuny (15] have pointed out – modern equipment is used extensively for "informal" household production. However, compared to their equivalents in the formal economy, purchase price will have a higher premium relative to performance, given that household systems of production are relatively small scale, with little technical interdependence, and with weak pressures of competition from alternative production systems.

The methods used by successful innovators to appropriate the benefits of their activities compared to their competitors will also vary. [14] For example, process innovations can be kept secret; some product innovations can be protected by natural and lengthy technical lags in imitation (e.g. aircraft), whilst others require parent protection (e.g. pharmaceuticals); and both product and process innovations may be difficult to imitate because of the uniqueness of the technological knowledge and skills in the innovating firm.

These ingredients are summarised in table 5, where column 1 defines the categories of firm, column 2 enumerates typical core sectors for such firms, columns 3–5 describe the determinants and the nature of the technological trajectories of the firms, and columns 7–10 identify some of the measured characteristics of these trajectories. We shall now go on to describe and discuss them in more detail.

[14] For more detailed discussion, see Taylor and Silberston [46], Scherer [50] and von Hippel [64–66].

3.2. *Supplier dominated firms*

Supplier dominated firms can be found mainly in traditional sectors of manufacturing, and in agriculture, housebuilding, informal household production, and many professional, financial and commercial services They are generally small, and their in-house R&D and engineering capabilities are weak. They appropriate less on the basis of a technological advantage, than of professional skills, aesthetic design, trademarks and advertising. Technological trajectories are therefore defined in terms of cutting costs.

Supplier dominated firms make only a minor contribution to their process or product technology. Most innovations come from suppliers of equipment and materials, although in some cases large customers and government-financed research and extension services also make a contribution. Technical choices resemble more closely those described in Salter's vintage model, the main criteria being the level of wages, and the price and performance of exogenously developed capital goods.

Thus, in sectors made up of supplier dominated firms, we would expect a relatively high proportion of the process innovations used in the sectors to be produced by other sectors, even though a relatively high proportion of innovative activities in the sectors are directed to process innovations. According to Scherer's data on the sectoral patterns of production and use of technology in the USA [51, table 2], the following sectors have such characteristics: textiles; lumber; wood and paper mill products; printing and publishing; and construction; in other words, precisely the types of sectors predicted by our taxonomy and theory. [15]

With our data on innovating firms in the UK, we are able to identify these and other characteristics of supplier dominated firms (as well as those of production intensive and science-based firms, described in subsections 3.3 and 3.4 below). Table 6 shows clearly the supplier dominated characteristics of textile firms. Before describing them, we shall define precisely the content of each of the columns of table 6, since tables 7, 8 and 9 present similar figures for the other categories of firms:

Column 1 defines the principal two digit sector of activity of the innovating firms.

Column 2 gives the percentage of innovations used in the sector that are produced by innovating firms principally in the sector. [16] It shows the degree to which firms in the sector develop their own process technology.

Column 3 shows the percentage of innovations produced by firms principally in the sector that are used in other sectors: in other words, the percentage of product innovations. [17]

Column 4 shows the size distribution of innovating firms principally in the sector. These figures are identical to those in columns 7, 8 and 9 of table 3.

Column 5 gives more detail on the nature of innovating firms' innovations outside their principal sector of activity. It breaks down the figures of column 1, table 4 between "vertical" and "concentric/conglomerate" technological diversification. These terms are taken from the writings of Ansoff [2] on business strategy. The "vertical" figure is the percentage of the innovations produced by innovating firms, that are outside the innovating firms' principal sector of activity, but used within the innovating firms' sector: it reflects the relative importance of technological diversification into the equipment, materials and components for their own production. The "concentric/conglomerate" figure is the percentage of the innovations that are both produced and used outside the principal sector of the innovating firms' activities: it reflects the relative importance of technological diversification into related and unrelated product markets.

Column 6 shows the origins of all the innovations in the sector, broken down between those produced by firms principally in the sector, those both produced and used by firms principally producing outside the sector (i.e. users of the output of the sector), and those from other sources. The figure in the first sub-column of column 6 adds up to 100 percent with the figure in column 5 of table 4.

[15] Scherer's data are incomplete for agriculture and for services, which we would predict to have similar characteristics.

[16] This percentage is not identical to the one in column 5 of table 2, since the former is based on the sector of the innovation, whilst the latter is based on the sector of principal activity of the innovating firm.

[17] This percentage is not identical to the one in column 1 of table 2, for the reasons given in footnote 16.

Table 6
Characteristics of innovations produced and used by firms producing principally textiles, and leather & footwear

Principal sector of firm's activity (2-digit)	Innovations used that are produced by firm		Innovations produced by firms that are used in other sectors		Size distribution of innovating firm (rows add up to 100%)			Innovations produced by firms in sector (No. produced)
	%	Number used	%	Number produced	10,000+	1000–9999	1–999	
(1)	(2)		(3)			(4)		
XIII Textiles	15.6	377	23.4	77	35.1	40.3	24.7	77
XIV&XV Leather and Footwear	48.9	45	56.0	50	44.0	18.0	38.0	50
Total: All sectors in sample	49.3	1401 [a]	64.0	2265	53.1	21.9	24.9	2265

Principal sector of firm's activity (2-digit)	% [b] firms' innovations outside principal sector of activity are		Innovations produced by firms in sector (No.)	% of innovations in firms' sector of activity produced by			Innovations produced in sector (No.)
	Concentric/ conglomerate	Vertical		Firms principally in the sector	Firms principally in other sectors that produce and use the innovation	Other	
	(5)				(6)		
XIII Textiles	3.9	20.8	77	63.8	2.2	34.0	91
XIV&XV Leather and Footwear	42.0	8.0	50	73.5	–	26.5	34
Total: All sectors in sample	20.3	11.2	2265	68.6	11.2	20.3	2265

[a] Includes only those innovations used in sectors specified in table 2.
[b] The sum of the two percentages is equal to that in column 1 in table 4.

In the case of textile firms, table 6 shows a high degree of dependence on external sources for process technology (column 2), a relatively small proportion of innovative activity devoted to product innovations (column 3), a relatively small average size of innovating firm (column 4), technological diversification mainly vertically into production technology with very little movement into other product markets (column 5), and a relatively big contribution to innovations in the sector by firms with their principal activities elsewhere, but not from sectors using textiles (column 6). More detailed data show the considerable importance to textile firms of machinery firms in supplying process technology, and of chemical firms in supplying process technology and in making innovations in the textile sector itself.

Table 6 also shows that innovating firms principally producing in leather and footwear do not fall so neatly into the category of supplier dominated firms. Certainly they are relatively small (column 4), and their users make a relatively small contribution to innovation in their principal sector of activity (column 6). However, they also produce a sizeable proportion of product innovations (column 3), as well as making a strong contribution to their own process technology (column 2), and they have a high degree of concentric/conglomerate technological diversification (column 5).

Close examination shows that all this technological diversification is into textile machinery innovations that find their main use in the textile sector. This pattern reflects the coding practice used by Townsed and his colleagues in their survey [60]. However, it does not reflect the fact that there is no separate SIC category for leather working machinery, that innovations in textile machinery have applications in the manufacture of leather goods, and that – although the main uses of the identified innovations in textile machinery were in the textile sector – they also found uses in the manufacture of leather goods. In other words, firms principally in leather goods were in fact making a major contribution to the development of their own process technology. In this case, they begin to join the production intensive category, which we shall now describe.

3.3. Production intensive firms

Adam Smith described some of the mechanisms associated with the emergence of production intensive firms, namely, the increasing division of labour and simplification of production tasks, resulting from an increased size of market, and enabling a substitution of machines for labour and a consequent lowering of production costs. Improved transportation, increasing trade, higher living standards and greater industrial concentration have all contributed to this technological trajectory of increasing large-scale fabrication and assembly production. Similar opportunities for cost-cutting technical change exist in continuous processes producing standard materials, where the so-called two-thirds engineering law means that unit capacity costs can potentially be decreased by 1 percent by every 3 percent increase in plant capacity.

The technological skills to exploit these latent economies of scale have improved steadily over time. In fabrication and assembly, machines have been able to undertake progressively more complex and demanding tasks reliably, as a result of improvements in the quality of metals and the precision and complexity of metal forming and cutting, and in power sources and control systems. In continuous processes, increased scale and high temperatures and pressures have resulted from improvements in materials, control instrumentation and power sources. [13]

The economic pressure and incentives to exploit these scale economies are particularly strong in firms producing for two classes of price-sensitive users: first, those producing standard materials; second, those producing durable consumer goods and vehicles. In reality (if not in various models of technical change), it is difficult to make these scale-intensive processes work up to full capacity. Operating conditions are exacting, with regard to equipment performance, controlling physical interdependencies and flows, and the skills of operatives. In such complex and interdependent production systems, the external costs of failure in any one part are considerable. If only for purposes of "trouble-shooting," trained and specialist groups for "production engineering" and "process engineering" have been established. As Rosenberg [42] has shown, these groups develop the capacity to identify technical imbalances and bottlenecks which, once corrected, enable improvements in productivity. Eventually they are able either to specify or design new equipment that will improve

[18] See Levin [22] for well documented examples.

productivity still further. Thus, one important source of process technology in production-intensive firms are production engineering departments.

Adam Smith also pointed out that process innovations are also made "... by the ingenuity of the makers of machines when to make them became the business of a peculiar trade" [54]. The other important source of process innovations in production-intensive firms are the relative small and specialised firms that supply them with equipment and instrumentation, and with whom they have a close and complementary relationship. Large users provide operating experience, testing facilities and even design and development resources for specialised equipment suppliers. Such suppliers in turn provide their large customers with specialised knowledge and experience as a result of designing and building equipment for a variety of users, often spread across a number of industries. Rosenberg [42] describes this pattern as "vertical disintegration" and "technological convergence". He draws his examples from metal-forming machinery; the same process can be seen at work today in the functions of production monitoring and control performed by instruments. These specialised firms have a different technological trajectory from their users. Given the scale and interdependence of the production systems to which they contribute, the costs of poor operating performance can be considerable. The technological trajectories are therefore more strongly oriented towards performance-increasing product innovation, and less towards cost-reducing process innovation.

The way in which innovating firms appropriate technological advantage varies considerably between the large-scale producers, and the small-scale equipment and instrument suppliers. For the large-scale producers, particular inventions are not in general of great significance. Technological leads are reflected in the capacity to design, build and operate large-scale continuous processes, or to design and integrate large-scale assembly systems in order to produce a final product. Technological leads are maintained through know-how and secrecy around process innovations, and through inevitable technical lags in imitation, as well as through patent protection. For specialised suppliers, secrecy, process know-how and lengthy technical lags are not available to the same extent as a means of appropriating technology. Competitive success depends to a considerable degree on firm-specific skills reflected in continuous improvements in product design and in product reliability, and in the ability to respond sensitively and quickly to users' needs.

The characteristics of large-scale producers and of specialised suppliers in the production intensive category are reflected in tables 7 and 8. Table 7 shows that, in our sample of innovations, firms with their principal activities in five of the two digit sectors in our sample have the characteristics of scale-intensive producers in the production intensive category: food products, metal manufacturing, shipbuilding, motor vehicles, and glass and cement. In these categories, innovative firms produce a relatively high proportion of their own process technology (column 2), to which they devote a relatively high proportion of their own innovative resources (column 3). Innovating firms are also relatively big (column 4), they have a relatively high level of vertical technological diversification into equipment related to their own process technology (column 5), and they make a relatively big contribution to all the innovations produced in their principal sectors of activity (column 6).

Table 8 shows the very different pattern in mechanical and instrument engineering firms. They also produce a relatively high proportion of their own process technology (column 2), but the main focus of their innovative activities is the production of product innovations for use in other sectors (column 3). Innovating firms are relatively small (column 4); they diversify technologically relatively little, either vertically or otherwise (column 5); and they do not make a relatively big contribution to all the innovations produced in their principal sector of activity, where users and other firms outside the sectors make significant contributions (column 6).

A more detailed examinations of the data at the three digit level shows that, within mechanical engineering, firms in all the product groups in the sample have a high proportion of their innovative resources devoted to product innovation, are technologically relatively specialised, and (with the exception of firms principally producing industrial plant) are relatively small. However, about 20 percent of the innovations are made by general engineering firms that produce in a range of mechanical engineering products, and the size distribu-

Table 7
Characteristics of innovations produced by firms producing principally in scale-intensive sectors

Principal sector of firm's activity (2-digit)	Innovations used that are produced by firm		Innovations produced by firms that are used in other sectors		Size distribution of innovating firm (rows add up to 100%)			Innovations produced by firms in sector (No. produced)
	%	Number used	%	Number produced	10,000+	1000–9999	1–999	
(1)	(2)		(3)			(4)		
III Food	58.8	68	48.8	78	79.5	7.7	12.8	78
VI Metal manufacturing	62.3	130	43.4	143	62.9	32.8	4.2	143
X Shipbuilding	64.5	90	34.8	89	61.8	34.8	3.3	89
XI Motor vehicles	45.7	221	36.9	158	72.2	20.3	7.6	158
XVI Glass and cement	68.3	63	50.6	87	74.7	16.1	9.1	87
Total: All sectors in sample	49.3	1401 [a]	64.0	2265	53.1	21.9	24.9	2265

Principal sector of firm's activity (2-digit)	% [b] firms' innovations outside principal sector of activity are		Innovations produced by firms in sector (No.)	% of innovations in firms' sector of activity produced by			Innovations produced in sector (No.)
	Concentric/ conglomerate	Vertical		Firms principally in the sector	Firms principally in other sectors that produce and use the innovation	Other	
	(5)				(6)		
III Food	16.7	14.1	78	83.1	3.1	13.9	65
VI Metal manufacturing	17.5	16.8	143	68.6	8.0	23.4	137
X Shipbuilding	21.3	37.1	89	71.2	13.5	15.4	52
XI Motor vehicles	12.6	20.9	158	82.0	1.6	16.4	128
XVI Glass and cement	13.8	18.4	87	81.9	5.6	12.5	72
Total: All sectors in sample	20.3	11.2	2265	68.6	11.2	20.3	2265

[a] Includes only those innovations used in sectors specified in table 2.
[b] The sum of the two percentages is equal to that in column 1 in table 4.

Table 8
Characteristics of innovations produced and used by firms producing production equipment

Principal sector of firm's activity (2-digit)	Innovations used that are produced by firm		Innovations produced by firms that are used in other sectors		Size distribution of innovating firm (rows add up to 100%)			Innovations produced by firms in sector (No. produced)
	%	Number used	%	Number produced	10,000 +	1000–9999	1–999	
(1)	(2)		(3)			(4)		
VII Mechanical engineering	55.1	169	82.6	536	24.3	36.9	38.8	536
VIII Instrument engineering	58.4	60	81.4	187	24.6	21.4	54.0	187
Total: All sectors in sample	49.3	1401 [b]	64.0	2265	53.1	21.9	24.9	2265

Principal sector of firm's activity (2-digit)	% [b] firms' innovations outside *principal sector of activity are*		Innovations produced by firms in sector (No.)	% of innovations in firms' sector of activity produced by			Innovations produced in sector (No.)
	Concentric/ conglomerate	Vertical		Firms principally in the sector	Firms principally in other sectors that produce and use the innovation	Other	
	(5)				(6)		
VII Mechanical engineering	15.1	0.9	536	68.1	15.3	16.8	633
VIII Instrument engineering	9.7	10.2	187	45.2	19.3	35.5	332
Total: All sectors in sample	20.3	11.2	2265	68.6	11.2	20.3	2265

[a] Includes only those innovations used in sectors specified in table 2.
[b] The sum of the two percentages is equal to that in column 1 in table 4.

tion of which is bigger than other mechanical engineering, being close to the average for the sample of innovations as a whole. In instrument engineering, innovations are produced by firms in a wide range of user sectors, as well as by firms principally in mechanical engineering and in electronic capital goods.

3.4. Science-based firms

The third category, namely science-based firms, was also foreseen (if not observed) by Adam Smith who spoke of the contribution ot technical of "... those who are called philosophers or men of speculation, whose trade it is not to do anything, but to observe everything; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects." From the data on innovations described above, science-based firms are to be found in the chemical and the electronic/electrical sectors. In both of them, the main sources of technology are the R&D activities of firms in the sectors, based on the rapid development of the underlying sciences in the universities and elsewhere.

As Freeman et al. [12] have shown, the development of successive waves of products has depended on *prior* development of the relevant basic science: in particular, of synthetic chemistry and biochemistry for the chemical industry; and of electromagnetism, radio waves and solid state physics for the electrical/electronic industry. Synthetic chemistry has enabled the development of a wide range of products, with useful structural, mechanical, electrical, chemical or biological characteristics, ranging from bulk materials replacing wood, steel and natural textiles, to specialised and expensive chemical and biological agents for medical or other uses. Post-war advances in the fundamentals of biochemistry are enabling the extension of these skills and techniques into biological products and processes.

Advances in electromagnetism, radio waves and solid state physics have enabled products and applications related to the availability of cheap, decentralised and reliable electricity, communications and (now) information processing, storage and retrieval. Applications in electricity vary from huge transformers to small motors within mechanical systems, in communications from expensive radar and satellite tracking systems to cheap transistor radios, and in information from huge computers to electronic wristwatches.

This pervasiveness has dictated the technological trajectories of firms in the science based sectors. The rich range of applications based on underlying science has meant that successful and innovative firms in them have grown rapidly, [19] and have had little incentive to look for innovative opportunities beyond their principal sector. Given the sophistication of the technologies and underlying sciences, it has been difficult for firms outside the sectors to enter them. The pervasive applications have also meant a wide variance in relative emphasis on production and process technology within each of the sectors, reflecting the different cost/performance trade-off for consumer goods, standard materials and specialised professional applications.

Firms appropriate their innovating leads through a mix of methods (i.e. patents, secrecy, natural technical lags, and firm-specific skills). Patent protection is particularly important in fine chemicals, with specific high grade applications, where the predominant product innovations can be quickly and cheaply imitated without it. [20] In addition, dynamic learning economies in production have been an important barrier to the entry of imitators in continuous process technology, large-scale assembly and – over the past 25 years – in the production of electronic components. According to Dosi [8], the particularly rapid rate and the form of technical change in electronic components involved a "paradigm shift." New firms have been able to enter the electronics industry, and to grow rapidly by aggressive product innovation coupled with the exploitation of steep dynamic economies of scale.

In the data on innovations in the UK collected by Townsend and his colleagues, characteristics of science-based firms emerge most clearly for those principally in chemicals, Table 9 shows that they produce a relatively high proportion of their own process technology (column 2), as well as a high proportion of product innovations that are used in other sectors (column 3). They are also relatively big (column 4), most of their technological diversification is concentric/conglomerate rather

[19] See, for example, the research of Rumelt [56] on the growth and diversification of US firms.

[20] See, in particular, the empirical studies of Taylor and Silberston [56].

Table 9
Characteristics of innovations produced and used by firms producing principally chemicals and electrical/electronic products

Principal sector of firm's activity (2-digit)	Innovations used that are produced by firm		Innovations produced by firms that are used in other sectors		Size distribution of innovating firm (rows add up to 100%)			Innovations produced by firms in sector (No. produced)
	%	Number used	%	Number produced	10,000 +	1000–9999	1–999	
(1)	(2)		(3)			(4)		
V Chemicals	77.4	71	78.0	290	82.4	7.9	9.6	290
IX Electrical and electronic engineering	80.2	107	60.9	343	65.9	12.2	22.0	343
Total: All sectors in sample	49.3	1401 [a]	64.0	2265	53.1	21.9	24.9	2265

Principal sector of firm's activity (2-digit)	% [b] firms' innovations outside principal sector of activity are		Innovations produced by firms in sector (No.)	% of innovations in firms' sector of activity produced by			Innovations produced in sector (No.)
	Concentric/ conglomerate	Vertical		Firms principally in the sector	Firms principally in other sectors that produce and use the innovation	Other	
	(5)				(6)		
V Chemicals	21.7	4.8	290	84.8	2.4	12.8	251
IX Electrical and electronic engineering	21.5	2.3	343	77.0	11.5	11.5	339
Total: All sectors in sample	20.3	11.2	2265	68.6	11.2	20.3	2265

[a] Includes only those innovations used in sectors specified in table 2.
[b] The sum of the two percentages is equal to that in column 1 in table 4.

than vertical (column 5), and they produce a relatively high proportion of all the innovations made in their principal sector of activity (column 6). More detailed data also show that, within the two digit chemical sector, the detergent product group has a relatively high proportion of process innovations; and that the technological diversification of chemical firms outside their principal two digit sector is mainly into instruments, machinery and textiles. According to table 9, firms principally in electronic and electrical engineering also have most of the predicted characteristics of science-based firms: a relatively high contribution to own process technology (column 2), relatively big innovating firms (column 4), mainly concentric/conglomerate diversification [21] (column 5), and a relatively big contribution to all innovations in their principal sector of activity (column 6).

However, the proportion of product innovations,,although absolutely large, is relatively small (column 3); more detailed data show that this cannot be explained simply by the preponderance of process innovations in broadcasting equipment, but also reflects a high proportion of innovations in electronic components that are produced and used by firms principally producing electronic capital goods. Furthermore, the relatively big contribution to the production of innovations made by firms with less than 1000 employees (table 9, column 4) reflects the increasing contribution made in the 1970s by such firms in the computer product group.

Finally, more detailed data suggest that large, diversified firms make a bigger contribution to innovations by science-based firms, than to those by specialised equipment supplies. As we saw in subsection 3.3, general engineering firms produced 20 percent of all the innovations in mechanical engineering. In chemicals, firms principally in general chemicals produced about 40 percent of the whole; and in electronics/electrical products, firms principally in electronics capital goods produced about 50 percent.

3.5. Technological linkages and changing trajectories

Linkages amongst the different categories of firm go beyond those described in the production

[21] More detailed data show that this is mainly into the mechanical engineering and scientific instruments sectors.

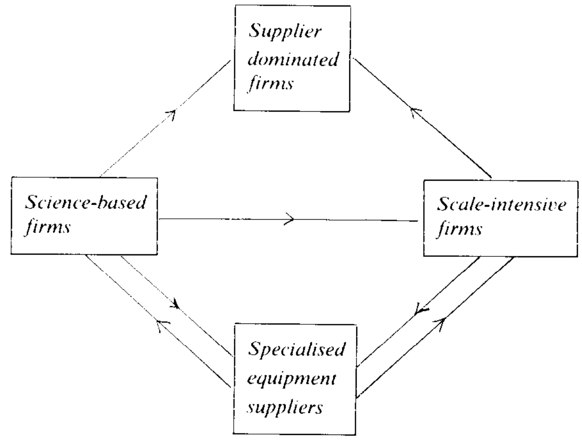

Fig. 1. The main technological linkages amongst different categories of firm.

intensive category (subsection 3.3. above). Figure 1 tries to represent the main technological flows emerging from our taxonomy and theory. Supplier dominated firms get most of their technology from production intensive and science-based firms (e.g power tools and transport equipment from the former; consumer electronics and plastics from the latter). Science-based firms also transfer technology to production intensive ones (e.g. the use of plastics, and of electronics, in the automobile industry). And, as we have seen, science-based and production intensive firms both receive and give technology to specialised suppliers of production equipment.

We have also argued that technological linkages amongst sectors can go beyond transactions involving the purchase and sale of goods embodying technology. They can include flows of information and skills, as well as technological diversification into the main product areas of suppliers and customers. Examples include the contribution of scale-intensive firms to the technology of their equipment suppliers and of chemical and electronics firms to innovations in textiles, scientific instruments and mechanical engineering.

Our data do not yet enable us to analyse if and how patterns of technical change in specific sectors change over time. We have hinted in subsection 3.3 that sectors can shift from the supplier dominated to the production-intensive pattern as a result of access to larger markets by individual firms, and of autonomous and induced improvements in capital goods: a contemporary example might be certain commercial and financial services, given producer concentration and rapid technical progress in information processing equipment. On the other hand, analysts like Utterback and Abernathy [70] would predict on the basis of their "product cycle" model that, where process technology has matured, sectors may shift from the production intensive to the supplier dominated pattern: for example, in bulk synthetic chemicals today, it is said that this focus has shifted from the chemical firms to their specialised suppliers of process equipment [6]. Whatever regularities in such change are eventually observed the above two examples suggest that trends in the *rate* of technological change will be an important explanatory variable. Of particular interest will be a systematic exploration of the effects of radical technological changes (e.g. solid state electronics) on prevailing paths and patterns of technical change. [22]

4. Some analytical implications

Our proposed taxonomy and theory have a number of implications for analysis of the nature, sources, determinants and economic effects of technical change. We shall now identify some of the most obvious ones, without pretending to be comprehensive in either breadth or depth of discussion.

4.1. Science and technology push versus demand pull

There is the continuing debate about the relative importance of "science and technology push" and "demand pull" in determining patterns of innovative activity, and in triggering innovative activity. As Mowery and Rosenberg [26] and others have pointed out, both technology push and demand pull are necessary for any successful innovation, and much of the debate about the relative importance of the two has been ill-conceived. Nonetheless, according to Schmookler [53], "demand-pull" has been a stronger influence than "science and technology push" on patterns of innovative activity, both across industry and over time. Across industry, he found a stronger statistical association between the volume of innovative activity in capital goods (as measured by patents) and the volume of investment activity in user industries, than between the volume of innovative activity and of output in the supplier industries. Over time, he found that changes in the volume of innovative activity followed changes in the volume of investment activity. Using a more comprehensive data base, Scherer [52] has recently confirmed the former of Schmookler's findings, but could find no evidence of a lag between investment and innovative activities.

In our taxonomy, the close relationship between investment in user sectors and innovative activities in upstream capital goods comes as no surprise. Investment activities in supplier dominated and production intensive firms are likely to stimulate innovative activities in both the production engineering departments of user firms, and the upstream firms supplying capital goods. [22] To the extent that these investment activities are planned in advance, and co-ordinated with the activities of production engineering departments of investing firms and with firms supplying production equipment, we would also expect – as Scherer found – that the lag between investment and innovative activities would tend to disappear.

However, we would not expect in our science-based firms a similarly neat and lagged correspondence between the volume of investment in user sectors, and of innovative activities. Recent research by Walsh [68] has shown that the emergence of major new product families in the chemical industry in the twentieth century has been *preceded* by an upsurge of scientific and inventive activities. Furthermore, Scherer [52] found that in materials sectors, in contrasts to capital goods, the statistical relationship between the volume of innovative activities and of investment in user sectors is much weaker; given the role of the chemical industry in developing synthetic *substitute* materials, this should not surprise us. Finally, Scherer [52] found that the relationship between the volume of innovative activities and the output of the supply industry becomes much stronger when account is taken of difference amongst sectors in scientific and technological opportunity – the relationship between the two being particularly strong in the

[22] For further discussion on the automobile industry see Anderson et al. [1]. More generally see Ergas [9].

[23] User sectors covered in Schmookler's analysis included petroleum refining, synthetic fibres, glass, sugar, tobacco, railroads, textiles and apparel, and timber and paper.

organic chemicals and electronics sectors, where we would expect science-based technical opportunities to be particularly strong.

4.2. Product versus process innovation

Our proposed theory also offers an explanation of the balance in different sectors between product and process innovation. We would expect the relative importance of product innovation in a sector to be positively associated with its R&D and patent intensity; and negatively associated with proxy measures of the scale and complexity of its process technology, such as its capital/labour ratio, average size of production plant, or sales concentration ratios.

The reasoning behind such an expectation runs as follows. In product groups with a high proportion of science-based firms, we would expect a relatively high R&D intensity, and a high proportion of product/market opportunities generated outside the product groups. The relationship should be even stronger between patent intensity and product innovation, given that – in addition to R&D activities – patent statistics reflect the innovative activities in small firms, and the production engineering departments of large firms, both of which are particularly important sources of product innovation in mechanical and instrument engineering. On the other hand, in sectors with a relatively high proportion of production intensive firms, we would expect both a realtively high proportion of resources to be devoted to process innovations, on the one hand, and relatively high capital intensities, size of plant and industrial concentration on the other.

As can be seen in the Appendix to this paper, the regression based on our (very imperfect) statistics are consistent with our expectations (E1, E2, E3). [24] The signs are correctly predicted and, in some equations, explanatory variables are significant at the 1 percent and $2\frac{1}{2}$ percent level. Only the capital–labour ratio has a low explanatory power in all of the equations that we tried, which may say as much about the problems of measuring capital as about the predictive powers of our theory.

[24] E1, E2 etc. refers to the relevant equations in the Appendix.

4.3. The locus of process innovation

Our taxonomy and theory also lead to expectations about the degree to which firms develop their own process innovations, or buy them from "upstream" suppliers of production equipment. In sectors with supplier-dominated firms, we would expect firms and production plant to be small in size, and innovations to come by definition from suppliers. In sectors with production intensive firms, we would expect firms and plant to be large in size, and a high proportion of process technology to be generated in-house. The same will be the case in science-based firms, especially in products involving continuous process and assembly technologies. In other words, we would expect a positive relationship between the proportion of a sector's process technology generated in-house, on the one hand, and the size of firms and of plant in the sector on the other.

Other writers have made related but somewhat different predictions, namely, that upstream equipment suppliers became relatively more important sources of process innovations as the absolute size of the market for the production process equipment grows. For Rosenberg [42], this reflects a greater division of labour in production resulting from a larger size of market. For Utterback and Abernathy [70], it reflects the large size and technological stability in firms at the later stages of the product cycle.

Von Hippel [67] and Buer [5] make predictions from a different basis, arguing that the balance between in-house development and recourse to upstream suppliers depends on the prospective benefits to be appropriated by the user of the production equipment. They argue that the benefits of appropriation by the user – compared to those of the supplier – increase with the degree of concentration in the user sector. The proportion of process technology developed in-house will therefore increase with the degree of user concentration. The data at present at our disposal does not enable an authoritative statistical test of these various hypotheses. Our measure of the proportion of process technology developed in-house is somewhat shaky, and we do not have comprehensive data on sources of process technology for sectors outside manufacturing. However, we can explore the relationship across sectors between the proportion of process technology developed in-house, on the one hand, and a range of variables reflecting the different hypotheses described above: average size of innovating firms, capital–labour ratio and average plant size (this writer's hypothesis); volume of investment in plant and equipment in equipment-using sectors (Rosenberg; Utterback and Abernathy); five firm concentration ratios in equipment using sectors (von Hippel; Buer).

This author's explanatory variables perform least well. Although the signs are all corectly predicted, none is statistically significant. However, the other hypotheses receive strong statistical confirmation (E4). The proportion of process technology developed by firms in the sector is negatively related to the absolute size of the market for process equipment, and positively to the degree of concentration of sales in the user sector.

4.4. Diversification

On the economic impact of technical change, our taxonomy and theory may also offer some insights into mechanisms of diversification, whether in terms of R&D and technology, or in terms of economic activity. Nelson [27] once suggested a positive relationship between the performance of basic research by firms and the diversity of their output, given that the uncertain results of basic research are more likely to find a use in a diversified firm than a specialised one. According to Scherer, however, the results of statistical analysis of the relationship between spending on basic research, and total R&D, on the one hand, and diversification, on the other "... have been mixed and to some extend contradictory" [49, p. 422].

According to our taxonomy, those related to total R&D are likely to be so, since we postulate a different causality, and predict an indeterminate and messy relationship between the variables. It is indeterminate (or, at least, non-linear), given that we predict relatively low levels of technology-based two digit diversification in sectors that are both R&D intensive (chemicals, instruments, and electrical/electronics), and low R&D spenders (supplier dominated). It is messy, given that the potential for technology-based diversification in science-based firms is much higher at the three digit than at the two digit level.

Furthermore, in both production intensive and supplier dominated firms the links between technology and production diversification may be weak. This emerges from a comparison of Hassid's data on production diversification [17] in British firms with those for technology in table 4. Production intensive firms diversify less in production than in technology, possibly because they do not exploit themselves all the opportunities open to them for technology-based diversification upstream into equipment supply. Textile firms, on the other hand, diversify more in production than in technology, possibly because of non-technological complementarities with other sectors.

However, we can, on the basis of our taxonomy, make some predictions about the factors determining potential technological paths of diversification in innovating firms, as a function of their principal activity. The relative importance of upstream (i.e. vertical) technological diversification into sectors supplying equipment is likely to be negatively associated with R&D intensity (which tends to provide technological opportunities concentrically or downstream), and positively associated with the scale and complexity of production technology (which induces innovative activities on production techniques and upstream equipment). Using the capital–labour ratio, and average plant size as proxy measures for scale and complexity of production technology, we find none of the expected statistical relationships at the three digit level. However, at the two digit level, and using the 20 firm concentration ratio as a proxy for scale and complexity of process technology, the statistical relations are as expected, and significant at the 1 percent level (E5).

Our taxonomy and theory may also help us better understand the links at the level of the firm between firm strategy and R&D strategy. Although much study has been devoted to the "tactical" problems of the management of activities necessary for innovations, [25] relatively little attention has been devoted to the "strategic" question of the role of technology in determining the future activities of the firm, and in particular its future product lines.

We propose a model that identifies the "technological trajectories" of firms as a function of their principal activities, and that enables us to predict possible paths of technological diversification across product lines and sectors. Given the wealth and detail of statistical data now becoming availa-

[25] See the survey by Rothwell [45].

ble on individual firms' technological activities, it will be possible to put our predictions to the statistical test by answering two questions. First, do firms with the same principal activities have statistically similar distributions of technological activity across product groups and technical areas? Second, are the distributions those predicted from our taxonomy and theory? Whilst we should not claim to be able to predict the specific competitive strengths and weaknesses of particular firms, we would at least be able to identify and explain the technological opportunities and constraints that in part govern their behaviour and choice.

However, we can predict with greater certainty that, at the level of individual firms, the degree of technological diversification will be positively associated with its size. This will reflect three mechanisms in our taxonomy and theory: first, large-scale production intensive firms procuding innovations upstream, principally in mechanical engineering and instruments; second, the possibilities open to small and specialised firms producing production equipment to remain small, competitive and technologically dynamic; third, the possibilities open to science-based firms for technological diversification beyond their principal three digit (but within their principal two digit) sector. Given these patterns of technological diversification in science-based firms, we would expect this relationship to be stronger at the three digit than at the two digit level.

Our data on innovations confirm these predictions. The size distribution of firms producing innovations outside their principal three digit sector is more skewed than average innovating firms towards large size: 69.9 (53.2) percent with 10,000 and more employees; 14.0 (23.2) percent with between 1000 and 9999 employees; 16.1 (23.7) percent with fewer than 1000 employees. [26] Across three digit sectors, we find a positive and statistically significant relationship (at the 5 percent level) between the degree to which innovating firms diversify technologically outside their three digit sector, and their average size in each sector.

Finally, we would predict on the basis of our taxonomy that, amongst science-based firms, relatively high levels of basic research will allow more innovations, more diversification beyond three to four digit sectors and more growth. In a recent study, Link and Long [24] found that the two most significant factors explaining differences amongst 250 US manufacturing firms in the proportion of sales spent on basic research were diversification at the four digit level, and having principal activities in science-based sectors. Although our proposed causality runs the other way, our results are consistent with those of Link and Long. Similarly, in a study of US firms in the petrochemicals industry, Mansfield [25] recently found a positive relationship between basic research as a percentage of value added, on the one hand, and the rate of growth of total factor productivity on the other hand. If one assumes further that growth of total factor productivitiy is positively associated with growth of output, then Mansfield's results are consistent with our taxonomy and theory.

4.5. Firm size and industrial structure

The causal links running from innovation to firm growth and to firm size are central to the recent research on the dynamics of Schumpeterian competition by Nelson and Winter [32]. They predict that, in industry with rapid rates of technical change, with uncertainty in the outcomes of investments in innovative activities, and with the strong possibilities for innovative firms to appropriate their innovative advantage, there are powerful tendencies over time towards the concentration of both production and innovative activities.

Our data and theory are consistent with these assumptions and outcomes for our science-based category of firms, but not for our supplier dominated or production intensive categories. In supplier dominated firms, any increase in firm size usually cannot be attributed to innovation, given that not much of it is generated in the sector, although increased size may enable (as described by Adam Smith) the introduction of more efficient process technology. In production intensive firms, innovation is associated with large and increasing size not, as Nelson and Winter [32] suggest, through the uneven exploitation amongst firms of a rich crop of new product/market opportunities, but through the search for increasing static scale economies in production. [27]

[26] Numbers in brackets refer to the percentage for all innovations: see table 4.

[27] See, for example, Levin [22].

The most important difference between Nelson and Winter's and our proposed model is the stable existence of small firms making innovations in production equipment and instrumentation. Rosenberg's description of textile machinery firms in the first half of 19th centry [42] is not very different – apart from the state of the technological art – from Rothwell's description of textile machinery firms in the second half of the 20th century [44]. As we have been in subsection 2.4, small, specialised and technologically dynamic equipment suppliers in mechanical and instrument engineering continue to live in symbiosis with even larger production intensive and science-based firms, and to confound trends towards Schumpeterian concentration. This is puzzling given that, as Rosenberg [42] has pointed out, common skills, techniques and know-how underlie all mechanical engineering products, just as they do in chemical-based and electrical/electronic-based firms. Why, then, have firms in these science-based sectors typically diversified and grown big on the basis of their accumulated skills, whereas those in mechanical and instrument engineering typically have not?

No definite answer can be given in this paper. Suffice here to suggest that explanations probably lie in sectoral differences in technology sources, users' requirements and appropriability. [28] Compared to chemical and electronic firms, those in mechanical and instrument engineering depend more on their customers for information and skills related to the operating performance, and to the design, development and testing of their products; they therefore can afford to remain small, but do not accumulate the same range and depth of technological skills. They also sell in markets that do not have such pronounced product cycle characteristics, and therefore have less market pressure to diversify. Finally, they find it more difficult to appropriate the benefits of their innovations, given the overwhelming importance of produce innovation, and relatively low barriers to entry, resulting from relatively small scale expenditures on product development, and the existence of many independent sources of skills and know-how in the production engineering departments of large firms.

[28] For a more detailed exploration of this question, see Ergas [10].

Innovative small firms are now to be found not only in instruments and mechanical engineering, but also in electronics: according to Townsend et al. the share of firms with up to 1000 employees increased in electronics in the 1970s. There has been one essential difference between innovative firms in instruments and mechanical engineering innovations, and those in electronics. Whilst the former have on the whole remained relatively small and specialised, a few of the latter became very large through precisely the mechanism of innovation and growth described by Nelson and Winter.

According to Dosi [8], new small firms can become big in a sector when there is a "paradigm shift" in technology, which alters radically the rate, direction and skills associated with a technological trajectory. However, whilst this might serve to explain the entry of new firms in the US electronics industry from 1950 to 1970, based on advances in solid state technology, it cannot explain the relative stability of structure of the world chemical industry over the past 60 years, in spite of successive waves of radical innovations – or "paradigm shifts" – growing out of synthetic chemistry.

The reasons for this difference must probably be sought once again in the nature of the scale barriers facing new entrants. In electronics (especially solid-state components and related equipment), static scale barriers are low, but there are very steep dynamic economies in production. This means that a small and successful innovator can quickly become very big, since imitators are chasing the innovator down steeply declined cost curves. In chemicals, on the other hand, there are high static scale barriers to new entrants: in bulk chemicals, there are big static economies of scale; in fine chemicals, there are systems of public regulation and control for new products that require heavy expenditures on testing and screening.

This discussion suggests that formal models of the dynamics of Schumpeterian competition, like those developed by Nelson and Winter, would more accurately reflect a varied reality in technological trajectories, if they were to explore a range of assumptions about new entrants and static and dynamic economies of scale; about pressures for market diversification; and about complementary relations between producers and users of capital goods.

5. Future perspectives

We began this paper with some dissatisfaction with existing conceptualisations of technical change. Based on systematic empirical data, we have tried to show why; and we have proposed another conceptualisation which, we hope, more accurately reflects the cumulative and varied nature of the technical change to be found in a modern economy. It is not necessary here to summarise the main conclusions of our analysis, since this is done at the beginning of the paper. Suffice to suggest some directions for the future.

First, our proposed taxonomy needs to be tested on the basis of complete sectoral coverage of the characteristics of innovations in Britain, of accumulated case studies, and of other data on innovative activities that become available. Our analysis suggests that R&D statistics do not measure two important sources of technical change: the production engineering departments of production intensive firms, and the design and development activities of small and specialised suppliers of production equipment. For reasons that are discussed elsewhere [37], it is probably that statistics on patenting activity capture innovative activity from these sources more effectively than do R&D statistics. The detailed information now becoming available on patenting activity by company should therefore enable a considerable step forward. As Rosenberg has observed [42], theoretical and practical advances have depended on good systems of measurement, and on accurate and comprehensive data. US patenting statistics could eventually enable the thorough econometric analysis that we considered and rejected at the beginning of this paper.

Second, our taxonomy itself needs to be modified and extended. Greater emphasis should be given to the exploitation of natural resources in the use of large-scale production equipment and instrumentation, [29] and therefore included in our production intensive category. And a fourth category should be added to cover purchases by government and utilities of expensive capital goods related to defence, energy, communications and transport.

Third, our taxonomy may have a variety of uses for policy makers and analysts. At the very least it may help to avoid general and sterile debates about the relative contribution of large and small firms to innovation, and the relative importance of "science and technology push" compared to "demand pull." It may also increase the value and effectiveness of micro-studies and micro-policies for technical change, by suggesting questions to ask at the beginning, and by putting results in a broader perspective at the end.

Fourth, the taxonomy and the theory may turn out to have more powerful uses. As we have seen in section 4 of this paper, they cast a different and perhaps fresh light on a number of important aspects of technical change: for example, the sources and directions of innovative activities; their role in the diversification activities of industrial firms and in the evolution of industrial structures; and the accumulation of technological skills and advantages within industrial firms. They may also give us a firmer understanding of the determinants of the sectoral patterns of comparative technological advantage that have emerged in different countries. [30] Nelson and Winter [31] have rightly observed that analysis of technical change has been "balkanised"; perhaps the concepts in this paper will help towards re-unification.

Fifth, our taxonomy and theory contain one obvious and important warning for both practitioners of policies for technical change, and academic social scientists concerned with is conceptualisation. Given the variety in patterns of technical change that we have observed, most generalisations are likely to be wrong, if they are based on very specific practical experience, however deep, or on a simple analytical model, however elegant.

For policy makers – many of whom come from the hard sciences and engineering – this means accepting that personal experience and anecdotal evidence from colleagues are an insufficient basis for policies that cover a range of technical activities. It also implies a need for sympathy towards systematic data collection on scientific and technological activities. Such data may be flawed in precision, but they do have the advantage of being comprehensive.

For the academic social scientists, one implica-

[29] See, for example, Townsend [61].

[30] For further discussion, see [38;40].

Table 10
Definition and description of variables

Symbol	Description	Source
Prop 3	Proportion of innovations used outside their 3 digit sector of production	Data bank on innovations
Prop 2	Proportion of innovations used outside 2-digit sector of production	Column 1, table 2
Inhouse 3	Proportion of innovations used in sector that are produced by sector/firms in the sector (3 digit)	Data bank on innovations
vertical	Proportion of innovations by firms principally in sector that are vertical diversification (2 digit)	Table 6–9, column 5
R/Y	Total R&D in manufacturing firms as a percentage of net output in 1975 (2 and 3 digit)	Business monitor, M014, 1979, table 20, (HMSO)
PSU	Average plant size (3 digit)	Information supplied by Dept. of Industry: based on industrial census, 1977
C_5	Proportion of sales in first five firms in 1970 (3-digit)	Business monitor, PA1002, 1975, table 9 (HMSO)
T/Y	Patents granted in the UK as a percentage of net output in 1975 (2 digit)	Same as R/Y; Townsend et al., table 11.1
D_{20}	Proportion of sales in first 20 firms in (2 digit)	Same as PSU
I	Expenditure on plant and machinery, 1970 (3 digit)	Same as C_5

tion is that analytical models of technical change are likely to become more complex and more numerous [31] Salter's vintage model of technical change [48] may be an accurate reflection of what happens outside industry and in traditional manufacturing; but in mass assembly and continuous process industries, the emphasis placed on investment and production as sources of technical change by such writers as Schmookler [53], Gold [15], Sahal [47] and even Kaldor [18] and Verdoorn [63] may be more appropriate; whilst the Schumpeterian dynamics of innovation, growth and concentration in science-based sectors are better reflected in the models and analyses of writers like Freeman [41;42], Nelson and Winter [32] and Dosi [8]. As we have seen in this paper, the variety in sectoral patterns of technical change was recognised by Adam Smith. Perhaps his is a tradition to which we should return.

[31] This same point is made by Gold [15].

Appendix

Some exploratory statistical analysis

As we pointed out in section 3 of this paper, inadequacies in data are one set of reasons why this paper is not econometric in nature. Some of the main inadequacies are as follows:

- The data bank on UK innovations, together with the other available data on industrial characteristics, allow at the most 11 data points at the two-digit level, and 26 points at the three-digit level;
- Whilst the data bank on UK innovations covers the period from 1945 to 1980, other systematic and detailed data on UK industrial activity began to emerge only at the end of 1960s;
- Some industrial statistics are not readily available in the degree of detail that suit the purposes of our analysis: for example, the patent intensity measure (T/Y) is not readily available at the three-digit level.

Table 11
Results of selected regressions

Equation	Dependent variable	Independent variables: sign and significance						$\bar{R}^2$	d.f.	F statistic
E1	Prop 3	+R/Y [b]	−PSU [a]					0.22	22	4.432 [b]
E2	Prop 3	+R/Y		$-C_5$ [b]				0.23	15	3.475
E3	Prop 2			$-D_{20}$	+T/Y [a]			0.54	8	6.872 [b]
E4	Inhouse 3			$+C_5$ [a]		−I [a]		0.56	15	11.786 [a]
E5	Vertical	−R/Y [a]		$+D_{20}$ [a]			−K/L	0.71	7	9.013 [a]

[a] Significant at 1% level.
[b] Significant at 2½% level.

Thus a proper statistical exercise, using the UK data base on innovations, will probably have to await the completion of sectoral coverage, and will require considerable statistical efforts to compile matching data from other sources. In the meantime, our statistical analysis can be only exploratory. The results discussed in section 4 of the paper are described in more detail in tables 10 and 11.

References

[1] M. Anderson, D. Jones and J. Womack, Competition in the World Auto Industry: Implications for Production Location, in: *The Future of the Automobile: A Trilateral View* (forthcoming, 1984).

[2] H. Ansoff, *Corporate Strategy* (Penguin Books, Harmondsworth, 1968).

[3] K. Arrow, Economic Welfare and the Allocation of Resources for Invention, in: *The Rate and Direction of Inventive Activity* (Princeton University Press, 1962).

[4] C. Berry, *Corporate Growth and Diversification* (Princeton University Press, 1975).

[5] T. Buer, *Investigation of Consistent Make or Buy Patterns of Selected Process Machinery in Selected US Manufacturing Industries*, Ph.D. dissertation, Sloane School of Management, MIT, 1982.

[6] Bureau de d'Economie Theorique et Appliquée, *Les Perspectives de la Chimie en Europe* (Université Louis Pasteur, Strasbourg, 1982).

[7] D. De Melto et al., *Preliminary Report: Innovation and Technological Change in Five Canadian Industries* Economic Council of Canada, Discussion Paper No. 176 (1980).

[8] G. Dosi, Technological Paradigms and Technological Trajectories, *Research Policy* 11 (1982).

[9] H. Ergas, Corporate Strategies in Transition, in: A. Jacquemin (ed.), *Industrial Policy and International Trade* (Cambride University Press, 1983).

[10] H. Ergas, The Inter-Industry Flow of Technology: Some Explanatory Hypotheses (mimeo) (OECD, Paris, 1983).

[11] C. Freeman, *The Economics of Industrial Innovation*, 2nd edition (Francis Pinter, London, 1982).

[12] C. Freeman, J. Clark and L. Soete, *Unemployment and Technical Innovation: A study of Long Waves and Economic Development* (Francis Pinter, London, 1982).

[13] J. Gershuny, *After Industrial Society*? (Macmillan, London, 1978).

[14] M. Gibbons and R. Johnstone, The Roles of Science in Technological Innovation, *Research Policy* 3 (1974).

[15] B. Gold, *Productivity, Technology and Capital* (Lexington Books, Lexington, MA, 1979).

[16] M. Gort, *Diversification and Integration in American Industry* (Princeton University Press, 1962).

[17] J. Hassid, Recent Evidence on Conglomerate Diversification in UK Manufacturing Industry, *The Manchester School* 43 (1976).

[18] N. Kaldor, *The Causes of the Slow Rate of Economic Growth of the United Kingdom* (Cambridge University Press, 1966).

[19] J. Kamin et al., Some Determinants of Cost Distributions in the Process of Technological Innovation, *Research Policy* 11 (1982).

[20] H. Kleinman, *Indicators of the Output of New Technological Products from Industry*, Report to US Science Foundation (National Technical Information Service, US Department of Commerce, 1975).

[21] J. Langrish et al., *Wealth from Knowledge* (Macmillan, London, 1972).

[22] R. Levin, Technical Change and Optimal Scale: Some Evidence and Implications, *Southern Economic Journal* 44 (1977).

[23] R. Levin and P. Reiss, Tests of a Schumpeterian Model of R and D Market Structure, in: Z Grilliches (eds.), *R and D, Patents and Productivity* (University of Chicago Press, 1984).

[24] A. Link and J. Long, The Simple Economies of Basic Scientific Research: A Test of Nelson's Diversification Hypothesis, *Journal of Industrial Economics* 30 (1981).

[25] E. Mansfield, Basic Research and Productivity Increase in Manufacturing, *American Economic Review* 20 (1980).

[26] D. Mowery and N. Rosenberg, The Influence of Market Demand upon Innovation: A Critical Review of Some Recent Empirical Studies, *Research Policy* 8 (1979).

[27] R. Nelson, The Simple Economics of Basic Scientific Research, *Journal of Political Economy* (1959).

[28] R. Nelson, *The Moon and the Ghetto* (Norton, New York, 1977).
[29] R. Nelson, Research on Productivity Growth and Productivity Differences: Dead Ends and New Departures, *Journal of Economic Literature* 19 (1981).
[30] R. Nelson, The Role of Knowledge in R and D Efficiency, *Quarterly Journal of Economics* (1982).
[31] R. Nelson and S. Winter, In Search of a Useful Theory of Innovation, *Research Policy* 5 (1977).
[32] R. Nelson and S. Winter, *An Evolutionary Theory of Economic Change* (Harvard University Press, Cambridge, MA, 1982).
[33] K. Oshima, in: B. Williams, *Science and Technology in Economic Growth* (Macmillan, London, 1973).
[34] K. Pavitt (ed.), *Technical Innovation and British Economic Performance* (Macmillan, London, 1980).
[35] K. Pavitt, Technology in British Industry: A Suitable Case for Improvement, in: C. Carter (ed.), *Industrial Policy and Innovation* (Heinemann, London, 1981).
[36] K. Pavitt, Some Characteristics of Innovative Activities in British Industry, *Omega* 11 (1983).
[37] K. Pavitt, R and D, Patenting and Innovative Activities: A Statistical Exploration, *Research Policy* 11 (1982).
[38] K. Pavitt, *Patterns of Technical Change: Evidence, Theory and Policy Implications*, Papers in Science, Technology and Public Policy, No. 3 (Imperial College/Science Policy Research Unit, 1983).
[39] K. Pavitt and S. Wald, *The Conditions for Success in Technological Innovation* (OECD, Paris, 1971).
[40] K. Pavitt and L. Soete, International Differences in Economic Growth and the International Location of Innovation, in: H. Giersch (ed.), *Emerging Technologies: Consequences for Economic Growth, Structural Change, and Employment* (JCB Mohr, 1981).
[41] E. Penrose, *The Theory of the Growth of the Firm* (Blackwell, Oxford, 1959).
[42] N. Rosenberg, *Perspectives on Technology* (Cambridge University Press, 1976).
[43] N. Rosenberg, *Inside the Black Box: Technology and Economics* (Cambridge University Press, 1982).
[44] R. Rothwell, *Innovation in Textile Machinery: Some Significant Factors in Success and Failure*, SPRU Occasional Paper No. 2 (University of Sussex, 1976).
[45] R. Rothwell, The Characteristics of Successful Innovators and Technically Progressive Firms, *R and D Management* 7 (1977).
[46]. R. Rumelt, *Strategy, Structure and Economic Performance* (Graduate School of Business Administration, Harvard University, 1974).
[47] D. Sahel, *Patterns of Technological Innovation* (Addison-Wesley, New York, 1981).
[48] W. Salter, *Productivity and Technical Change*, 2nd Edition (Cambridge University Press, 1966).
[49] F. Scherer, *Industrial Market Structure and Economic Performance* (Rand McNally, 1981).
[50] F. Scherer, *The Economic Effects of Compulsory Patent Licensing* (New York University, 1977).
[51] F. Scherer, Inter-industry Technology Flows in the United States, *Research Policy* 11 (1982).
[52] F. Scherer, Demand Pull and Technological Invention: Schmookler Revisited, *Journal of Industrial Economics* XXX (1982).
[53] J. Schmookler, *Invention and Economic Growth* (Harvard University Press, Cambridge, MA, 1966).
[54] A. Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations* (G. Routledge (1895 Edition)).
[55] L. Soete, A General Test of Technological Gap Trade Theory, *Review of World Economics* 117 (1981).
[56] C. Taylor and A. Silberston, *The Economic Impact of the Patent System* (Cambridge University Press, 1973).
[57] D. Teece, *The Multinational Corporation and the Resource Cost of International Technology Transfer* (Ballinger, New York, 1977).
[58] J. Toledano, A Propos des Filières Industrielles, *Revue d'Economie Industrielle* (1978).
[59] M. Teubal, *The Role of Technological Learning in the Exports of Manufactured Goods: The Case of Selected Capital Goods in Brazil and Argentina*, Discussion Paper No. 82.07 (Maurice Falk Institute for Economic Research in Israel, 1982).
[60] J. Townsend, F. Henwood, G. Thomas, K. Pavitt and S. Wyatt, *Innovations in Britain Since 1945*, Occasional Paper No. 16 (Science Policy Research Unit, University of Sussex, 1981).
[61] J. Townsend, Innovation in Coal-Mining Machinery, in K. Pavitt [34].
[62] M. Utton, *Diversification and Competition* (Cambridge University Press, 1979).
[63] P. Verdoorn, I Fattori che Regolaro lo Suiluppo della produttivita de lavoro, *L'Industrie* (1949).
[64] E. von Hippel, The Dominant Role of Users in the Scientific Instrument Innovation Process, *Research Policy* 5 (1976).
[65] E. von Hippel, A Customer-Active Paradigm for Industrial Product Idea Generation, *Research Policy* 7 (1978).
[66] E. von Hippel, The User's Role in Industrial Innovation, in: B. Dean and J. Goldhar (Eds.), *Management of Research and Innovation*, Studies in the Management Sciences, Vol. 15 (North-Holland, Amsterdam, 1980).
[67] E. von Hippel, Appropriability of Innovation Benefit as a Predictor of the Source of Innovation, *Research Policy* (1982).
[68] V. Walsh, Invention and Innovation in the Chemical Industry: Demand Pull or Discovery Push?, *Research Policy* (1984), forthcoming.
[69] J. Woodward, *Management and Technology* (HMSO, London, 1958).
[70] J. Utterback and W. Abernathy, A Dynamic Model of Process and Product Innovation, *Omega* 3 (1975).