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by

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Industry-specific competencies and converging technological systems: evidence from patents

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**Abstract**

Utilising patent data, this empirical paper draws upon the notion of technological path-dependence at the industry level and finds that industry-specific competencies have endured strongly over the twentieth century - industrial sectors patent most in their corresponding technological fields, and differences in overall technological profiles remain quite marked. However, in an increasingly complex technological environment, paradigms developed within one industry may spill over into others as firms seek to absorb them. Eventually, after long periods of time the spillovers may become large as firms go beyond the development of new applications of their core technologies into the absorption of new modes of technological behaviour originally developed elsewhere. Technological profiles therefore show a pattern of 'convergence' under such conditions. Firms unable to attain this second stage of spillover may become 'industrial dinosaurs'.

*Keywords:* technological competencies, spillovers, convergence

*JEL classification:* O30, O39, L60

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## 1. Introduction

This paper considers technological competencies and the extent to which they remain industry-specific over time. We define a technological competency as the ability to create and use a particular field of technology effectively, which is gained through extensive experimentation and learning in its research, development and employment in production. We take industries to be defined primarily by the products (goods and services) they produce.

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Industries, and the large firms included within them, have typically produced multiple products over the past century or more (Chandler, 1990). The production of each of these products typically requires multiple technologies, as explained further below. The relationship between technologies, as ‘inputs’, and products, as outputs, in large firms - and *a fortiori* in industries - is hence normally not one-to-one or even one-to-many, but many-to-many (Piscitello, 1998). As a result, the products firms’ produce can be identified strongly with a particular industry, whilst the range of technologies the firm uses to product this output is probably less industry specific. With this in mind, we aim to examine whether there has been a process of ‘convergence’ in technological competencies between large firms in different industries.

A review of the existing literature might leave the reader feeling ambivalent as to whether technological competencies are industry-specific or whether there should be any convergence in technological competencies across industries. On the one hand, it has been suggested that technological activity is highly industry-specific (Patel and Pavitt, 1994a, 1997). That is, industries are characterised by a certain set of technologies which are common to, and dominant for, those firms operating within that industry. These technologies may be labelled as ‘core’ technological areas for that industry. For example, it would be expected that most chemical firms, even when broadly defined, would have some skill in technologies such as ‘distillation processes’ and that electrical firms would have skill in the technologies associated with ‘electricity, conductors and insulators’. However, we probably would not expect an electrical firm to possess great competencies in distillation processes, nor the reverse. As these differences between firms and industries are expected to persevere over time, we label this the ‘path-dependency’ view. In this view, most spillovers of technology between firms would arise within specific industries.

On the other hand, literature at the firm level has recognised that firms now operate in a broader range of technological areas than historically and that there has been corporate technological diversification (Fai and Cantwell, 1999). This view has been most commonly allied with the notion of ‘long waves’ in cross-industry technological ‘paradigms’ (e.g. Freeman et al., 1982; Dosi, 1988; Freeman and Louçã, 2001). For example, whilst Henry

Ford's Model T relied primarily on mechanical technologies (relating to engines, gearing etc.) and chemical technologies (relating to fuel consumption, metallurgy etc.), present-day Ford models combine these with digital and electronic systems for the more sophisticated control of temperatures, fuel regulation, braking systems, etc. In addition, the adoption of programmable computers on the vehicle assembly line, in order to make rapid changes in the models produced and their components, alters the structure of process technologies involved. Thus in both product and process technologies, the new digital-electronic 'paradigm' surfaces as an important technological input in the vehicle industry as well as in its original home in the electrical-electronic industry. Since the 'long wave' view supposes that all industries will come to be influenced sooner or later by these new technological paradigms, we can label this as a process of technological convergence between industries.

These two interpretations are however rather crude, and when read in a more considered and subtle light the two literatures are not really at odds. For example, the 'path-dependency' view does not deny the importance of new fast-growing technologies, but the way it encompasses the idea is through assuming the continuation of a division of labour between firms and industries producing those technologies, and firms and industries using them. Conversely, the 'long wave' view does not reject substantial path-dependency in the medium term, as its protagonists explore the conditions for conflict between old and new paradigms (Freeman and Perez, 1988). The 'technological convergence' view also has the capacity to accept that there may be a continual division of labour in the face of new technologies and that much of the actual manufacturing of such component parts might be outsourced or developed via strategic alliances. However, the proviso could be made that these represent only the formal organisational modes which carry out such activities. Firms participant in such partnerships still need to be able to integrate the underlying technologies into a compatible whole. Thus, at the very least, the car manufacturer (in this example) will need a level of 'absorptive capacity' (Cohen and Levinthal, 1989)[2] to combine the sub-technologies

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[2] Cohen and Levinthal (1989) "argue that the ability of firms to evaluate and utilize outside knowledge is a function of their level of prior related knowledge. This prior related knowledge (as is reflected by patenting activity in this case) confers an ability to recognize the value of new information, assimilate it and apply it to commercial ends" (Levinthal, 1996).

embodied in constituent parts into a marketable vehicle. Hence, during this process the firm is likely to diversify in technological terms. Furthermore, this increasing technological diversity at the firm level, when aggregated, ought to be reflected in part at the industry level. In other words, increasing technological diversity within and across firms should be reflected in a changing technological structure at the industry level, with spillovers occurring across industry boundaries. It seems then that the ambivalence that might arise is due to a perceived gap between these two literatures, rather than these literatures falling into divided camps. The gap however already has a number of tentative bridges built across it from both a theoretical and a historical perspective.

Within theory, Schumpeter's work brought the notions of path-dependency and diversification together as it progressed and developed over time. The 'early-Schumpeter' view (e.g. Schumpeter 1911/1934) is highly path-dependent and supposes that the advent of new products and technologies leads to the 'creative destruction' of older products and hence of the firms which produce them. Any firms that survive become 'industrial dinosaurs', though they may endure an undistinguished old age before they eventually collapse. The 'late-Schumpeter' view (e.g. Schumpeter, 1943) instead suggests the adaptability of large older enterprises, and their ability to initiate as well as passively absorb new advances. In this case the notion of path dependence remains, but it is a less rigid concept and allows for technological diversification to occur within the same enterprise. These have their counterpart in the management literature in the coexistence of, yet contrast between, 'competence-destroying' and 'competence-enhancing' technologies (e.g. Tushman and Anderson, 1986).

The historically based literature also gives support to these views. There has been a strong focus on the persistent specificity of competencies at the firm level (e.g. Patel and Pavitt, 1994a; Cantwell and Fai, 1999), which is widely regarded as symptomatic of path-dependency in firms' technological structures. The notions of 'core competencies' and of 'sticking to the knitting', which dominated management thinking in the area in the 1980s and early 1990s (Peters and Waterman, 1982; Prahalad and Hamel, 1990), attest to the practical as well as theoretical significance of such ideas.

However, in the course of the twentieth century, new scientific areas such as electronics and genetics have emerged, new technological fields have been driven forward by firms (Cantwell and Fai, 1999), and consumers have demanded new products like increasingly sophisticated software. According to this view, the world has become more technologically complex[3] - opportunities are dispersed across a broad range of technological areas, technologies are increasingly used as complements, new technologies are used to extend the life of older ones, and firms that seek to exploit these opportunities have become more multi-technological (Granstrand and Sjölander, 1990; Oskarsson, 1993)[4]. As a result, many once relatively simple artefacts or processes no longer draw upon just a few technologies, but upon a widened range of technologies (Feldman and Audretsch, 1995).

As well as firms developing technological competencies in new areas, their existing technological capabilities may, over time, come to have multiple uses both within and outside their primary industrial sector of activity (Langlois and Robertson, 1995, pp. 40-41). This represents an enlarged range of applications or uses of the firm's outputs. Again, the result might be that the technology profiles of firms from various industries become more similar over time, blurring the industry-specificity of technologies[5]. Because of lack of data, in this paper we have to infer the breakdown between the widening range of technologies required for an existing range of products and the widening adoption of existing technologies in products new to the firm (cf. von Tunzelmann, 1995, ch. 8).

The notion of General-Purpose Technologies (GPTs), recently popularised (e.g. Bresnahan and Trajtenberg, 1995; Helpman, 1998), draws on this latter view of inter-industry spillovers. The GPT notion tends to stress technologies as key artefacts, such as the steam engine or the laser, which in the fullness of time come to be adopted in several 'application sectors'. The

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[3] On the notion of 'technological complexity' and its varied meanings, see Wang and von Tunzelmann (2000).

[4] Note that individual authors may at various times ascribe to both arguments, e.g. Granstrand et al. (1997).

[5] Andersen (1998) presents two models in connection with the greater dispersion of technological opportunities across broadly defined technological groups over time. The first model argues that technological opportunities became less concentrated or more interrelated due to the intra-technological-group dispersion of technological opportunities (i.e. applying existing technologies to new areas). The second argues that inter-technological-group convergence in technological opportunities is responsible for the phenomenon (i.e. bringing in new technologies from areas not usually associated with the industry). The first model was found to be applicable to the period 1920-1960, whilst the second was applicable to the period 1940-1990.

long wave view accepts that these GPTs may well be strongly represented among the spillover technologies, but raises the wider the issue of new knowledge about how and where to advance technologies and to solve the problems raised by existing technologies. For example, the production of microprocessors remains concentrated in specialist producers using expensive dedicated equipment, but simpler or application-specific (ASIC) chips may be embedded in advances made by users and reflected in patenting by user industries. The latter are led more generally to solving technological problems through miniaturization and information technology as encouraged by advances in semiconductors, i.e. the new paradigm spills over to them as well. Hence the GPT view stresses the demand side for new applications of potentially generic technologies, whereas the long wave view adds this to a greater emphasis on the supply or input side, of major breakthroughs in scientific or technological thinking.

The progression of a technological paradigm as described above would suggest that paradigms are characterised by a period of rapid technological growth through innovation in a particular industry, followed by a period of somewhat slower growth, forming an ‘S-curve’ of technological development (Andersen, 2000, ch. 4) - see Figure 1. However, when the industry in which the technology was most immediately relevant is positioned in the section of its pathway where there are decreasing returns, there may come a greater diffusion of the technology to other industries. This has implications for our expectations about patterns of technological convergence over time at the industry level, where technological convergence is regarded as the process by which different industries come to share similar technological bases.

[Figure 1 here]

When the rate of innovation in a new technological area is highest, technological innovation will occur predominantly in the industry that can most easily and readily exploit the opportunities which arise, which is the industry which has this area as its ‘core competence’. This will coincide with increased technological divergence between industries (or at least a slowing in the degree of convergence), and over this period, industry-specific path-dependency dominates. However, at some point there will come a point of inflexion and the growth rate of the technology will slow in the initial industry, but in some cases its pervasiveness across industries may rise as the diffusion process occurs (see Figure 2). As the technology diffuses, we would expect increased technological convergence between industries (or at the minimum a decrease in the degree of divergence between industries).

[Figure 2 here]

Therefore, there are many sources of literature which hint that technological diversification within firms, path-dependency and technological convergence between industries are not necessarily opposing or conflicting forces but that they can in fact work together in the same direction, perhaps in a sequential manner. However this has not been formally demonstrated in any general way. In this paper we attempt to make their linkages explicit through the use of empirical data. After outlining the data and indicators used to measure technological specialisation in section 2, this paper shows that the 'profiles' of technological competencies are quite distinct between broad industrial sectors (section 3). These endure, in the sense that firms and industries continue to be recognisable from their technological profiles, even though these change over time. Evidence presented in section 4 shows that there has been technological convergence between industries, as on average these changes have been in similar directions though at different points of time. In section 5, the paper focuses on the technologies themselves and aims to discover which technologies experienced the greatest degrees of convergence or divergence between industrial sectors over different historical time intervals. Our summary and conclusions are given in section 6.

## 2. Data and methodology

### *2.1 Patents as a technological indicator*

This paper relies upon patent data as a technological indicator. Whilst it is not our intention to review the plethora of arguments for or against the use of patents as a proxy measure for technology here, some justification of the use of patents and their ability to reveal the presence of technological convergence is required prior to examining the database this paper utilises.

Patents have frequently been compared with R&D expenditures as technology proxies, though often seen as complements rather than substitutes, with R&D measuring technology ‘inputs’ and patents technology ‘outputs’.[6] Pakes and Griliches (1984) found that R&D and patents are well correlated in cross-sectional analysis, but more weakly related in longitudinal analysis. Where the two differ, arguments against just using R&D focus on the diminishing returns to R&D expenditure, and the tendency for R&D to over-emphasise a concentration of technological activity in large companies whilst underestimating the technological activity of smaller firms (Pavitt, 1988; Griliches, 1990; Patel and Pavitt, 1991; Archibugi and Pianta, 1992). Patents, on the other hand, are criticised for disguising both inter-industry and inter-firm differences in the propensity to patent and differing levels of significance of each patent in relation to technological advance. Yet the same arguments can be levelled at the use of R&D based measures: is not the pharmaceutical industry more likely to invest in R&D than the steel industry?; do not companies within the same industry spend different proportions of their sales earnings on R&D?; is it not the case that many R&D projects lead to dead-ends whilst others lead to radical new products and processes? Others might argue that some firms prefer secrecy to patenting, and that patents more accurately represent invention rather than innovation. However, Mansfield (1986) found that firms apply for patents for 66-87% of their patentable inventions and Archibugi (1992) reports that of those inventions that are patented, 40-60% become innovations. Patents also have a number of strengths which cannot be found in other measures. For one, patents afford accurate and detailed identification of the technologies which are used within specific R&D projects. Secondly, patents are suitable for the analyses involving long time-frames whereas R&D data were not recorded extensively

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[6] This is different from the question of whether technology, however measured, can be considered an ‘input’ into *production*. Here we are referring to inputs and outputs in the generation of *technologies*.

prior to the late 1950s, and much later for most countries outside the USA (Griliches, 1990). Where the US Patent Office introduces new patent classes, all previously registered patents are reclassified accordingly. Acs and Audretsch (1989) tested the reliability of patents as a proxy for innovative activity and concluded that they are a fairly good, although imperfect, proxy. Thus, whilst the debate regarding use of patents data goes on:

> "We have a choice of using patent statistics cautiously and learning what we can from them, or not using them and learning nothing about what they alone can teach us" (Schmookler, 1966, p. 56).

As noted in section 1 above, industries can be identified by the type of output (i.e. goods and services) the firms which comprise them produce. However, most large companies have engaged in at least some development in most of the general spheres of technological activity irrespective of the industry in which they operate; e.g. chemical firms may develop patents for specialised equipment for their specific purposes which may be more akin to a mechanical technology than chemical technology. Fortunately, patents reveal the ownership of the patent, and so the patents any corporation holds will highlight what range of technological interests the firm has; therefore we can trace through patents how the technological areas of interest to firms in different industries change over time. With increasing technological complexity in products and production processes (von Tunzelmann, 1995) and the presence of widely dispersed technological opportunities (Andersen, 2000), we might expect growing inter-firm and inter-industry division of labour in patenting, if the strict 'path-dependency' view is valid, or alternatively growing intra-firm and intra-industry diversity in patenting, if the 'technological convergence' hypothesis holds. The 'S-curve' argument would predict a sequence in which the former was followed by the latter.

### *2.2 The database*

In view of the consistency of US screening and the importance of the US market, it has frequently been asserted that US patent data provide the most useful basis for international comparisons of technological change (e.g. Soete, 1987; Pavitt, 1988). The University of Reading database, compiled by Professor John Cantwell, is drawn from patents registered at the US Patent and Trademark Office between 1890 and 1995. It has been used to examine technology and innovation at the firm (Patel and Pavitt, 1997; Cantwell and Fai, 1999), industry (Cantwell and Santangelo, 2000), regional/national (Zander, 1997; Cantwell and Janne, 1999, 2000). A diagrammatic summary of the construction of the Reading database is given in the Appendix, Figure A1. We stress, consistent with the arguments presented above, that the database is organised in a manner which recognises that, whilst firms may be separated into broadly defined and distinct industrial areas according to their primary sector of production, the range of technologies in which these firms are active may be far more diverse. Firms, therefore, have been classified into industrial groups in a manner distinct from the way in which the patents in various technological areas (received by those firms) have been allocated (see the Appendix for details).

In the Reading patent database, a total of 867 companies or affiliates were traced historically, together comprising 284 corporate groups or firms. They were identified in one of three ways: firms which accounted for high levels of US patenting after 1969; firms which were amongst the historically largest 200 industrial corporations in the US, Germany or Britain, from the lists provided by Chandler (1990); and finally, companies which featured prominently in the US patent records in earlier years, including US firms with at least 30 patents per year and all European firms granted at least five patents per year. Births, deaths, mergers and acquisitions as well as the occasional movement of firms between industries have been taken into account within the database. On the basis of the primary type of *products* produced, four major industrial sectors have been identified here: i) Chemicals [chemicals, pharmaceuticals, artificial fibres, coal and petroleum products]; ii) Electrical [electrical equipment, office equipment (including computing)]; iii) Mechanical [food, drinks, metals, mechanical engineering, paper and paper products, printing and publishing, non-metallic mineral products, professional and scientific instruments, other manufacturing]; and iv) Transport [motor vehicles, aircraft (aerospace), other transport equipment, rubber and plastic products (tyres)]. Collectively, these will be referred to as the CEMT industrial sectors.

From the database, a sample of firms was selected. Firms had to possess an accumulated stock of at least 225 patents by 1930 to reduce small-number problems, particularly in the earlier part of the period. Furthermore, we required firms whose corporate patenting activity could be traced across the period 1930-1990, despite having merged, de-merged or changed company name etc. As corporate patenting took off in the interwar period, a cut-off point earlier than 1930 would significantly reduce the number of firms considered in this paper. This gave 32 firms or corporate groups in 1930 (6 chemical, 9 electrical, 11 mechanical, and 6 transport firms), although the changing composition of the corporate groups alters the number of firms over time (see Appendix Table A1). The selection criteria do not allow us to pick up firms which possessed less than 225 patents in 1930, but which may have grown over the period of study and become significant patenters today (unless they subsequently merged with one of our selected firms). Taking different samples of firms at different periods would inhibit our ability to trace historical technological convergence.

The trade-off is that we may be left with some ‘industrial dinosaurs’, of the kind noted in our Introduction. Seventeen of the 32 firms however were in the Fortune 2000 top 500 global or US companies, and a further 7 could be traced as major business units or subsidiary divisions of such companies. Only three have broken up more or less beyond recognition in recent times. For the purposes of analytical continuity, firms are consolidated into the corporate groups as they were in 1930 (e.g. IG Farben - now Bayer, BASF, Hoechst; Swiss IG - now Novartis) and all firms are referred to under their 1930 name (see Appendix Table A1)

Despite their economic significance, there are two major problems in using patents for economic analysis: classification and variability (Griliches, 1990). The classification problem is dealt with in the structure of the database itself. The US Patent Office classifies patents into many classes (in excess of 300 in the mid 1950s) and many more subclasses (>50,000). As can be seen from Figure A1b, the 399 patent classes (as they were in 1990) have been aggregated to various levels. This paper works primarily at the technological classification level of 56 technological fields. A full list of these fields, and their further aggregation into five broad technological areas, can be found in Table 1. An inspection of this list provides some controversial categorisations but care has been taken as far as possible to allocate sub-classes of patents to the relevant technological field. For example, patents belonging to some of the subclasses that fall in US patent class ‘refrigeration’ comprise a group that has been assigned to the technological field ‘chemical processes’ in the chemical technology area, whilst others have been allocated to ‘general electrical equipment’ in the electrical/electronic area. Likewise, the field ‘synthetic resins and fibres’ in the chemical area comprises the patent classes ‘chemistry carbon compounds’ and ‘synthetic resins or subclasses of natural rubbers’, whilst the field ‘rubber and plastic products’ in the transport area relates to the patent classes ‘resilient tyres and wheels’ and ‘plastic and non-metallic article shaping or treating’. Similar exercises have been applied to fields like ‘office equipment’, ‘calculators and typewriters’, etc., which are electronically based (including personal computers and the electronic parts of printers), versus older office machinery which goes into the fields of ‘printing equipment’ and other ‘specialised machinery’.

In the preparation of the data for this paper, different levels of aggregation were compared, and it was found that the general results were fairly insensitive to reasonable variations in the level of disaggregation[7]. The 56 fields can be further aggregated into five very broad technological areas as set out in Table 1, defined as the Chemical, Electrical/Electronic, Mechanical, Transport and Other areas (CEMTO). It is important to emphasise that, despite the similarity of names, the CEMT *industrial* sectors are different in kind from the CEMTO *technological* areas.

[Table 1 here]

The second issue, that of variability, arises in both the impact of individual patents and the propensities to patent (inter-firm and inter-industry). The problem of impact is largely overcome through the use of cumulative patent stocks. Technological activity is measured using a count of patents granted in the period 1901-90, which are accumulated into stocks over the period 1930-90 using the perpetual inventory method. Straight-line depreciation for the separate contribution

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[7] The 50,000 or so sub-classes of the 399 USPTO classes are not examined here, but the great majority of these disaggregations have little or no economic meaning.

of each new patent is allowed for over a thirty-year period, this being taken as the normal expected lifetime of the capital in which the knowledge is partially embodied[8]. In other words a patent awarded in year t has a weighting of 30/30, a patent awarded in t-30 has a weighting of 1/30, and a patent awarded in year t-31 has a value of zero. There will, of course, be considerable variation around this average depreciation measure, but the older a patent is, the less it is weighted in the patent stock.

Inter-firm differences are not a major issue here as the analysis is conducted at the level of the industrial sectors, whilst the effects of inter-industry differences in the propensity to patent are reduced as far as possible through the use of the Revealed Technological Advantage (RTA). The RTA index has been used to measure the relative specialisation of corporate and national technological competencies (Cantwell, 1991, 1993; Patel and Pavitt, 1995). It alleviates a degree of the inter-industry difference to patent in different fields by weighting an industrial sector's patenting in a particular field by the overall propensity of that industrial sector to patent in general, and is given by the following formula:

$$RTA_{ik} = (P_{ik}/(\Sigma_k P_{ik})/((\Sigma_i P_{ik}/(\Sigma_{ik} P_{ik}) \qquad (1)$$

$P_{ik}$ = the number of patents held in technological field i by broad industrial sector k.

The value of the index centres around unity, such that a value greater than one in a particular technological field indicates that the industrial sector possesses a relative technological advantage in that field, i.e. it is technologically competent in that technological field relative to other industrial sectors. A value of less than one indicates relative disadvantage.

## 3. Industry-specific competencies and path-dependency

[8] There is of course considerable variance in the expected capital life expectancy as between different items, but it is unlikely that the average changes much over time. This is different from the lifetime of the patent itself, which for US patents has generally been 17 years (Griliches, 1990, p. 1662).

When analysing industry-specific competencies, the use of a relative measure such as the RTA exposes the analysis to distortion through small-number problems. For this reason, the range of patents to be examined was narrowed. For a field to be included in this part of the analysis it had to possess an accumulated patent stock of 100 patents or more in 1930 (pat30>100 - see Table 1). As we can see from the last row of Table 1, this criterion eliminated many fields in each of the four industrial sectors, as compared with the theoretical total of 55 fields in each case[9]. An alternative criterion was to require there to be 500 or more patents in a field in 1960, which allowed in more fields for the chemical industry but less for the others. Both criteria show indications of a 'diagonal' relationship between the industry and the technological fields in which it does the majority of its patenting. The chemical industry patents primarily in chemical technologies, similarly the electrical/electronic industry is important in developing most of the electrical/electronic fields, mechanical in most mechanical fields and the transport industry in transport technological fields.

However, at the same time, we can see that the chemical industry is also technologically strong in the mechanical and transport fields pertaining to equipment; the electrical/electronic industry is strong in many mechanical technologies, as is the transport industry (which is not surprising). We also see that the mechanical industry is active in several of the fields in all four of the other technological areas (CETO). This already suggests that technologies are less industry-specific than might be expected from the industry-specificity argument. In this case, the pervasiveness of mechanical technologies to all industrial sectors is clear (albeit to different degrees)[10]. This is reflected in the presence of mechanical technologies in the profiles of all four industries, and on the other side of the same coin, by the more limited diversification of the mechanical industry into non-mechanical technological fields. While some changes are evident between the 1930 criterion and that for 1960, the table nevertheless gives some support to the path-dependency view that the overall technological profiles of different industries are rather distinct and persist over time. Such path-dependency in the evolution of industrial technological competencies is further demonstrated by the strength of the correlation in the RTA distribution

[9] There were no patents in nuclear reactors in 1930.

[10] Patel and Pavitt (1994b) demonstrated the pervasiveness of older mechanical technologies.

(in the technological fields selected on the pat30>100 criterion) between the years 1930-60, 1960-90 and 1930-90 (see Table 2).

[Table 2 here]

From Table 2 it is clear that industry-specific competencies for each industrial sector endure even over time horizons of sixty years, although this is less so for the transport sector in 1930-60, and for both the mechanical and the transport sectors in 1930-90. However, over this time frame, industry-specific competencies in historically significant technological fields do erode.

The erosion in the persistence of industry-specific competencies may work in two possible directions. One would be that the industry is becoming more technologically focused over time. The chemical industry would become increasingly strong in chemical technologies, and weaker in, say, the mechanical technologies which it had earlier developed. This would mean that the industries would appear to become more technologically divergent. The alternative is that industries are becoming more technologically diversified. In this view, the chemical industry still patents predominantly in chemicals, but increasingly patents in mechanical technologies, suggesting that the industries are becoming technologically convergent. The correlations in Table 2 themselves are therefore equally compatible with the alternative long-wave view. Moreover, the findings in this section hinge upon the adequacy of the rather arbitrarily chosen criteria for cutting off small numbers of patents in order to avoid major biases in the RTA calculations. The proportion of technological fields common to more than one industry can turn out to be small if these criteria are too stringent. Further study is thus required.

## 4. Inter-industry technological convergence

According to the technological convergence view, as time progresses industries move out of technological fields which were of importance in a past period, into other areas which are of importance to a later period. Using patent stocks in all of the 56 fields allows us to capture the essence of this type of technological shift. For these reasons, our analysis in this section considers all 56 technological fields, rather than some sub-sample based on historical criteria.

Table 3 shows the estimated inter-industry correlation ($\hat{\rho}$) matrices that have been compiled using patent stock counts across all 56 technological fields. It also provides more detail with respect to the timing of any convergence between industrial sectors by considering them across 15-year rather than 30-year intervals. As the RTA is not being considered here but rather the correlation of patent stocks, the problem of the distorted emphasis of the importance of certain fields through small-number problems is not an issue. A positive coefficient reflects that a pair of industries place the 56 fields in more or less the same order of technological importance; a negative value indicates that they rank the technological fields in the opposite order. The greater the actual value of the coefficient, the greater the degree to which the relationship holds.

[Table 3 here]

In 1930, only the mechanical and transport industries were significantly correlated (figures in bold type). Given their common bases in mechanical engineering, this result might have been expected. By 1945 a significant but low correlation arises between the electrical and the transport industrial sectors. This might be indicative of the advances being made in the military transport industries at that time, with respect to the improvement of instrumentation and transmission systems etc. In 1960 some convergence occurs between the technologies which the chemical and mechanical industrial sectors are developing. This corresponds well with Rosenberg and Landau (in Rosenberg, 1994), who comment that, although chemical engineering as a discipline emerged in the early twentieth century, specialised engineering firms (SEFs) played a critical role after World War II. As these firms learned more about the field through working for various chemical firm clients, they are likely to have become more innovative at this time.[11] By 1975 the electrical and mechanical industries also became similar to the point of statistical significance, probably through the application of electrical

[11] Freeman found that by the 1960s nearly three-quarters of all major new chemical plants were engineered, procured and constructed by specialised plant contractors (Rosenberg, 1994, p. 200).

and electronic processes to formerly mechanised equipment, so that either industry might plausibly be producing it. No further new significant correlation between pairs of industries occurred by 1990. However, over the whole 60 years, each time a pair of industries became statistically significant, this coefficient grew stronger in each subsequent period; the only (and minor) exception being the correlation between the chemical and mechanical industrial sectors between 1975 and 1990, which weakened marginally.

Table 3 therefore supports the proposition that technological convergence has emerged between broadly defined industries over the period 1930-90. The illustrations provided are based on what is described in the literature on the history of technology and industrial histories. However, in order to provide some details on the sources of any such convergence we need to examine what the pervasive paradigms in each industry were over the period. Furthermore, we need to examine whether any of these have spread from their industry of origin into wider usage elsewhere, as a complementary or enabling technology which provided new opportunities for innovation in the second industry.

## 5. Identifying emerging technological paradigms and fields of convergence

### *5.1 Emerging paradigms*

An indication of the changing paradigms considered in the literature referred to in the Introduction are reflected in patent data is given in Table 4. This table ranks technological fields according to their proportionate increases in patent stocks over the specific 15-year intervals (1930 to 1945, etc.). Emerging technological paradigms are assumed to show up in fast growing patenting, and therefore visible by obtaining high rankings. The rankings are, of course, influenced by the level of the patent stock in the initial year, so a high rate of growth from a tiny initial base may not mean very much. Thus ‘semiconductors’ get top ranking in 1930/45, i.e. in the years *before* the invention of the transistor, and again in 1945/60; but by 1975/90 when the microprocessor revolution is in full sway, they are almost halfway down the table, because the base (1975) is so much higher than in 1930 or 1945 (as indicated in the first two data columns of this table).

[Table 4 here]

Allowing for this, one can see the relatively rapid growth of many chemicals fields in 1930/45 and 1945/60, though some like ‘distillation processes’ then drop away. The rise of ‘pharmaceuticals and biotechnology’ (which has subsequently transformed the chemical industry) gets top ranking in 1975/90. In the electrical/electronics area, the case of ‘semiconductors’ has just been mentioned, but computing equipment grows predictably rapidly after 1945. After 1960 there is some switch of emphasis to electronic products including consumer electronics, with ‘telecommunications’ also picking up after 1975. The mechanical technologies tend to have a middling performance, with the weaker ones like ‘textile machinery’ reflecting the slow growth of user sectors. Much the same is true in the transport area, but there is a resurgence of growth in the ‘internal combustion engine’ after 1975 mainly reflecting fuel crises (the impact of fuel efficiency in patents data from the 1970s is confirmed by Meliciani, 1998). ‘Nuclear reactors’ are another odd case, because of having no patents at the outset. Overall, and allowing for the exceptions mentioned, the rankings together with the changes in overall shares (the difference between the first two data columns) do appear to reflect prevailing views about the most striking technological and industrial changes[12]. But do technological paradigms originating in one industry eventually pervade into other industries and so lead to the convergence of technological systems?

### *5.2 Identifying areas of industrial technological convergence*

To identify areas of industrial technological convergence, we need to relate the areas and fields of convergence to the paradigm shifts previously adumbrated. Table 5 provides an assessment of the spread of technological paradigms across industries by restricting the attention to the 12 fastest-growing fields over the whole period 1930-1990 (subject to the restriction that the share in the total patent stock in 1990 was greater than 0.5%, cf. Table 4). Certainly a number of these (at least) are closely identified with usual notions of what

[12] For further analysis of similar data, the reader is referred to Andersen (2000).

constituted paradigmatic change over this interval - ‘pharmaceuticals and biotechnology’, ‘semiconductors’, ‘data processing equipment’, ‘rubber and plastic products’, etc.

[Table 5 here]

The figures in the table represent rankings of percentage-point increases, relative to all technological fields (there were altogether 55 of these fields in 1930/45 and 56 thereafter with the addition of ‘nuclear reactors’). Initially the impact of these fast-growing fields is predominantly in the chemical industry, and as the majority of them (7 out of 12) are classified as chemicals technologies, this reflects a concentration in the associated industry. Over time, the median rankings for the fast-growing fields rise in both electrical/electronics industries and in the transport industries (see bottom row). The rankings for electronic technologies are not surprisingly the highest in the electrical sector, but there is also some increased impact on other sectors of fast-growing fields, especially in regard to ‘data processing equipment’. The mechanical sector overall shows less indication of convergence, although there is some indication of it for the most obvious new technologies.

The table on the whole thus supports Andersen’s notion of an S-shaped pattern of initial divergence and then subsequent convergence, at least so far as the fastest-growing technologies are concerned. Nevertheless, the pattern in Table 5 is far from being as smooth as might have been expected. Table 6 looks at the full range of technological fields, not just the fastest growing. In this table, we have computed the median scores of the percentage-point increases of each technological area in each industrial sector, at 15-year intervals. The medians are derived from the equivalent scores for the 56 technological fields. The fastest patenting increase of a broad technological area for the chemical industry in 1930/45 would score 1, and so on. As a group, the median of ‘other’ technologies increased fastest in this industry in 1930/45 while the median of ‘chemicals’ technologies increased slowest (top-left data panel). We have also computed the quartile deviation (QD) around these rankings to reveal the amount of dispersion. In the example given, though the ‘other’ technologies increased fastest on average in the chemical industry in 1930/45, there was some spread around the median, as shown by a 2= ranking of the QD; conversely, though the 'chemicals' technologies increased slowest on average, there was a very high dispersion around this median, so *some* chemicals technologies would have risen quite rapidly.

[Table 6 here]

The rows for the chemical industrial sector in Table 6 show that chemical technologies were not growing very rapidly on average in the first sub-period (1930/45), as just stated. By this time, what might be termed the 'second generation' of chemical technologies was maturing and the 'third generation' (pharmaceuticals etc.) still relatively small. The median score was thus low, but as just pointed out some chemical technologies being developed by the chemicals firms were growing quite rapidly. The high median score recorded by 'other' technologies mainly represent users of chemicals (food products etc.). So by this stage, one is seeing the diffusion of chemical technologies to user industries being incorporated within the technological ambit of the supplier companies. Electrical technologies also score quite highly in the chemical industry, indicating the fusion between electrical and chemical technologies previously mentioned.

This pattern generally intensifies over the next two sub-periods, down to 1975. The median score for the chemical technologies themselves even declines, and the dispersion remains very high, as fast-growing and slow-growing fields coexist. In the final sub-period, the 'third generation' of chemicals really comes through, and pulls chemical technologies up to first place in terms of the median, though with a continuing high dispersion.

In the electrical/electronics industrial sector, electrical technologies appear to have been less mature in the first sub-period than were the chemicals technologies, as reflected in the high median score for electrical technologies in their own industry at that time (median = 11, ranking = 1). Examination of the individual technological fields suggests that some electrical technologies had indeed matured, e.g. electric lamps, but new branches were still emerging. Thus the dispersion was high (QD = 29, rank = 5). The pattern of maturation and dispersion as found for the chemical industries becomes more evident in the following periods, especially 1960/75. As with chemicals, the rise of new-generation electrical technologies (especially information technology and semiconductors) leads to a high median and high dispersion in the years after 1975. The effect of users for the electrical industries is less clearly apparent than for chemicals, except in some branches of mechanical engineering. The high ranking for chemicals technologies in later sub-periods does, however, probably reflect the orientation of use of electrical technologies to chemical purposes rather than the reverse, if we take into account the individual technological fields involved (not shown in the Table).

Mechanical technology inputs continue to be important throughout this period into many user fields, as Patel and Pavitt (1994b) have shown. The relative importance of the technological areas in the mechanical industry thus mostly reflects the ‘demand-pull’ of growth of user activities (we noted earlier the decline of branches of mechanical engineering in branches like textile machinery where demand was comparatively stagnating). The ‘third generation’ of chemicals however had less impact on mechanical firms than other radical technological departures, as one might predict from the nature of pharmaceutical production processes. The rise of knowledge-based industries seems bound to amplify this effect in the recent past and future. The high level of electrical technologies in this sector, especially in later years, appears to be brought about by the adoption of the electromechanical paradigm in the mechanical engineering industries, rather than by supplying machinery to electrical activities; so representing the upswing of the ‘S-curve’.

Finally, the transport sector is inherently more ‘downstream’ than the others considered, so that the impact of paradigm changes ‘upstream’ is quite strongly in evidence here, e.g. the importance of electrical technologies. The low growth of transport technologies themselves, together with low dispersion, suggests that the sector was technologically quite mature from the beginning of our time span. However, as there is no aircraft or similar company among the included companies, our results may be somewhat biased as a reflection of the sector as a whole.

To summarise Table 6, we find that the ‘S-shape’ pattern appears confirmed by these data for the companies of our dataset. Maturing technologies showed low median scores with low dispersion. At this stage, the main fields of growth tend to be in user activities, as applications of the upstream technologies progress steadily. As new generations of technologies appear, they show up mainly as high dispersion in the associated sectors (chemical technologies in the chemical industry, etc.). It can take 30-60 years for the new generations to dominate the growth of technologies in the associated industry. Meanwhile, the impact begins to spill over into other user activities, so bringing eventual convergence in those respects.

## 6. Summary and Conclusions

This paper sought to discover whether there has been a growing overlap of the technological areas in which different industrial sectors are operating, or whether technological profiles at the industry level remain specific and distinct. The recognised trends of increasing technological complexity and the increasing emergence of 'multi-technology' firms would suggest that the technological profiles of firms have become more diversified, but whether these phenomena have been pervasive enough to blur industry boundaries was uncertain. Moreover, the erosion of an existing profile of technological competencies does not by itself indicate whether firms and industries retreated into their heartland 'core competencies', or instead diversified into areas of overlap through the rise of new technological paradigms with generic implications.

The paper first finds that the overall technological profiles of the four broadly defined industrial sectors indeed remained highly distinct and somewhat persistent over the period 1930-90, and that, by and large, the industrial sectors tended to patent most in their corresponding technological fields, as judged by RTAs (Tables 1 and 2). Such a measure confirms the 'path-dependency' view related to enduring industry specificity.

However, when explored more generally, across all the technological fields, much stronger support emerged for the alternative view of an increased convergence between the industrial sectors (Tables 3 to 6). Both views set out in our Introduction can therefore be supported from the historical evidence. If we envisage a matrix with 'Industrial sectors' forming columns and the 'technological fields' forming rows; path-dependency is evident when looking at the levels of patenting across the technological fields within each industrial sector (i.e. within columns) whilst technological convergence over time is more apparent when looking at changes in patenting within the technological fields across all industrial sectors (i.e. within rows). In terms of firm behaviour, as the core technologies of firms matured, they would mainly look downstream to user applications as a first way of diversifying. However the advent of new technological paradigms, initially in their own industry and later elsewhere, would eventually redirect their efforts. This confirms the existence of an ‘S-shape’ which Andersen (2000) has found at the technological level, here in behaviour at the level of large firms. The situation emerging from our results for firms is as set out in Figure 2, with the flatter sections corresponding to periods mainly devoted to developing applications, and the steeper finer dashed section to absorbing inter-industry spillovers. The latter follow as a counterpart to the former; for example, firms in the transport industry may first buy in data-processing hardware from the electronic industry, but subsequently develop their software in-house. The relationship is suggested by the linking arrow in Figure 2. Firms which fail to absorb the inter-industry spillovers (new paradigms) become consigned to ‘dinosaur’ status even though they may continue to develop downstream applications; a pattern that was beginning to emerge at the very end of our observation period.

The paper therefore extends the work recently undertaken on ‘General-Purpose Technologies’, which emphasises new applications of generic technologies, to the ‘long wave’ context of incorporating new technological paradigms into the ways in which firms develop new processes and products. The spillover effects of innovations that are made in one industrial sector may be positive, and contrary to some views eventually become large when applied (with some adaptation) to other industrial areas.[13] However the time intervals involved may be very long, as firms balance path-dependency on the one side against increasing technological complexity from the absorption of new technological areas on the other.

[13] It might be that inter-industrial spillovers are largely of principles contained within innovations, rather than the actual innovations themselves. The paper by Feldman and Audretsch (1995) is a good review of the issues involved, as noted in our Introduction.

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Figure 1: S-shaped path of a technological trajectories within an industry specific paradigm

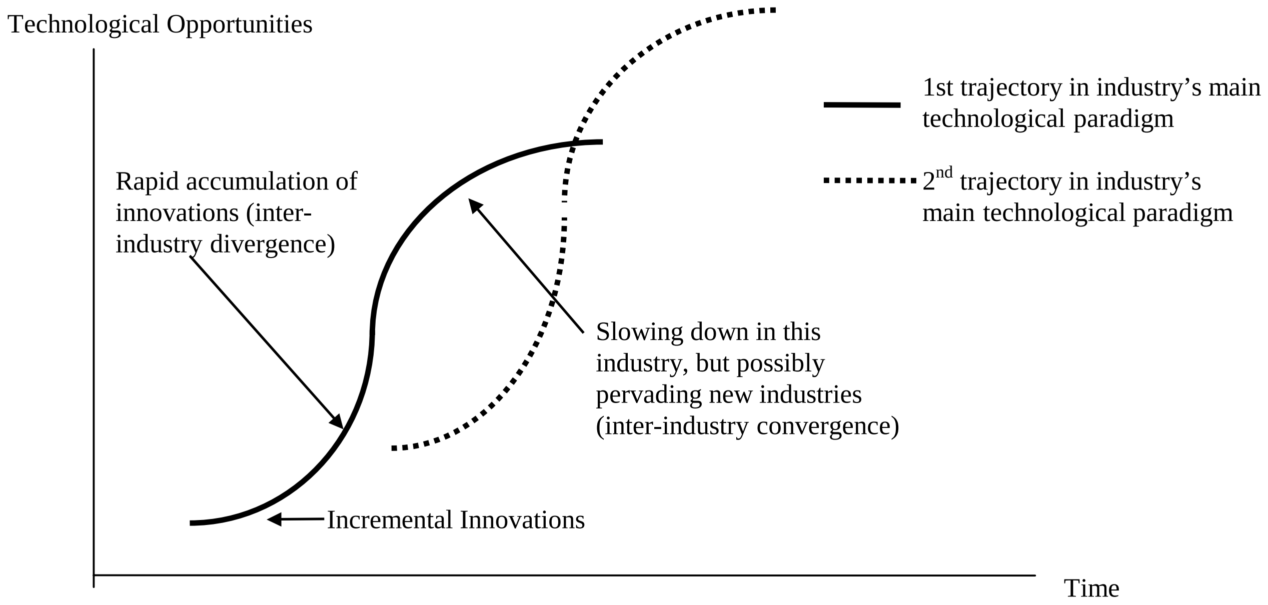

Figure 2: S-shaped paths for firms in particular industries, adopting industry-specific and spillover technologies

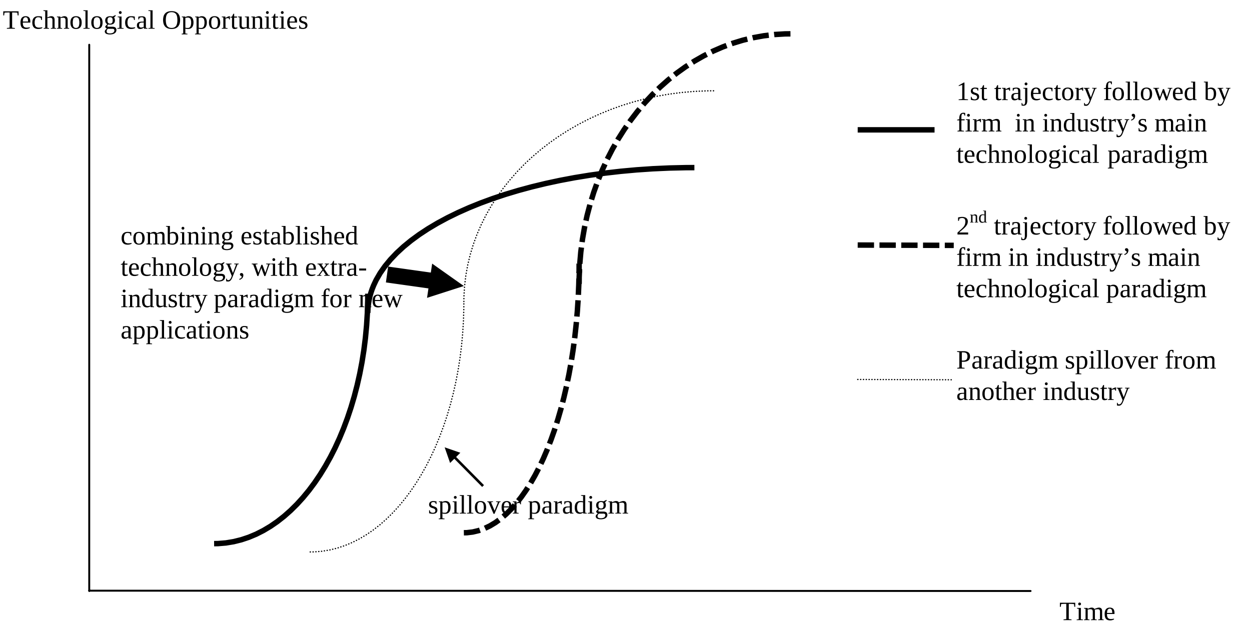

Table 1: Technological areas and fields and industrial sector competencies

| | | *Industry* | | | | *Industry* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *C* | *E* | *M* | *T* | *C* | *E* | *M* | *T* |
| *Tech. Area CEMTO* | *Tech. field* | pat30> 100 | pat30> 100 | pat30> 100 | pat30> 100 | pat60> 500 | pat60> 500 | pat60> 500 | pat60 >500 |
| Chemical | chemical processes | X | X | X | X | X | X | X | X |
| | distillation processes | | | | | X | | | |
| | inorganic chemicals | X | | | | X | | | |
| | agricultural chemicals | | | | | | | | |
| | explosives | | | | | | | | |
| | photographic chemistry | | | | | X | | X | |
| | cleaning agents etc. | X | | X | | X | | | |
| | disinfecting + preserving | | | | | | | | |
| | synthetic resins + fibres | X | | | X | X | | X | X |
| | bleaching + dyeing | X | | | | X | | | |
| | other organic compounds | X | | | | X | | X | |
| | pharmaceutical + biotech. | X | | | | X | | | |
| | coal + petroleum prods. | X | | | | X | | | |
| Electrical/ electronic | telecommunications | | X | | | | X | | |
| | other elect. communicns. | | X | | | | X | | |
| | special radio systems | | X | | | | X | | |
| | image + sound equipment | | X | | | | X | | |
| | semiconductors | | | | | | X | | |
| | office equipment + DP | | X | | | | X | | |
| | calculators + typewriters | | X | | | | X | | |
| | photographic equipment | | | X | | | | | |
| | illumination devices | | X | | | | X | | |
| | elect. devices + systems | | X | X | | | X | X | X |
| | other general elect. equip. | X | X | X | X | X | X | X | X |
| Mechanical | metallurgical processes | | X | X | X | X | X | | X |
| | misc. metal products | | X | X | X | X | X | X | X |
| | metalworking equip. | | X | X | X | | X | X | X |
| | chemical + allied equip. | X | X | X | X | X | X | X | X |
| | building material equip. | | | X | | | | | |
| | material handling equip. | | X | X | | X | X | X | |
| | construction equip. | | | | | | | | |
| | mining equip. | | | | | X | | | |
| | agricultural equip. | | | X | | | | X | |
| | food + tobacco equip. | | | | | | | | |
| | textile machy. | | X | X | | X | X | X | |
| | papermaking equip. | | | | | | | | |
| | printing equip. | | | X | | | | | |
| | woodworking machy. | | | | | | | | |
| | other special machy. | | X | X | X | X | X | X | X |
| | other general ind. equip. | X | X | X | X | X | X | X | X |
| | elect. lamp manufacturing | | | | | | | | |
| | power plants | | X | | | | | | X |
| | other instruments | | X | X | X | X | X | X | X |
| Transport | internal combustion | | | X | X | | | | X |
| | motor vehicles | | | | X | | | | |
| | aircraft | | | | X | | | | X |
| | ships + marine | | | | | | | | |
| | railway equip. | | X | X | | | | | |
| | other transport equip. | | X | X | X | | | | |
| | rubber + plastic prods. | | | | X | X | | | |
| Other | nuclear reactors | | | | | | | | |
| | textiles + leather | | | X | | | | | |
| | wood products | | | | | | | | |
| | building materials | | X | X | | X | X | X | |
| | food + tobacco products | | | | | | | | |
| | other + non-industrial | | X | X | | | X | | |
| | | **(11)** | **(24)** | **(22)** | **(15)** | **(22)** | **(21)** | **(16)** | **(14)** |

Table 2: The persistence of industry-specific competencies (value of $\hat{\rho}$)

| Broad industrial sector | $RTA_{1960}$ on $RTA_{1930}$ | $RTA_{1990}$ on $RTA_{1960}$ | $RTA_{1990}$ on $RTA_{1960}$ | $RTA_{1990}$ on $RTA_{1930}$ |
|---|---|---|---|---|
| | (pat30>100) | (pat30>100) | (pat60>500) | (pat30>100) |
| Chemical | 0.914 | 0.977 | 0.972 | 0.902 |
| Electrical/electronic | 0.923 | 0.987 | 0.986 | 0.913 |
| Mechanical | 0.861 | 0.817 | 0.894 | 0.695 |
| Transport | 0.688 | 0.977 | 0.984 | 0.689 |

Note: All correlations are significant at the 1% level.

Table 3: Inter-industry correlation coefficient matrices and technological convergence between industries

| Year | | C | E | M |
|---|---|---|---|---|
| 1930 | E | -.039 | - | - |
| | M | -.010 | .205 | - |
| | T | .033 | .213 | **.539** |
| 1945 | E | -.081 | - | - |
| | M | .141 | .143 | - |
| | T | .032 | **.330** | **.646** |
| 1960 | E | -.059 | - | - |
| | M | **.373** | .239 | - |
| | T | .087 | **.414** | **.656** |
| 1975 | E | -.025 | - | - |
| | M | **.399** | **.305** | - |
| | T | .133 | **.471** | **.693** |
| 1990 | E | .007 | - | - |
| | M | **.353** | **.367** | - |
| | T | .131 | **.498** | **.717** |

Note: Figures in bold are statistically significant from zero at the 5% level

Table 4: Ranking of the 56 technological fields in terms of their relative percentage increase in patent stocks over a specific 15-year interval.

| | | Share of total patent stock, % | | Ranking in proportionate increase | | | |
|---|---|---|---|---|---|---|---|
| *Tech. area* | *Tech. field* | *1930* | *1990* | *1930/45* | *1945/60* | *1960/75* | *1975/90* |
| Chemical | chemical processes | 1.72 | 4.35 | 19 | 13 | 16 | 11 |
| | distillation processes | 0.07 | 0.20 | 3 | 11 | 54 | 47 |
| | inorganic chemicals | 1.19 | 1.21 | 32 | 35 | 23 | 24 |
| | agricultural chemicals | 0.05 | 0.85 | 8 | 3 | 12 | 2 |
| | explosives | 0.24 | 0.11 | 42 | 49 | 10 | 56 |
| | photographic chemistry | 0.33 | 1.82 | 6 | 20 | 9 | 16 |
| | cleaning agents etc. | 1.21 | 2.68 | 7 | 22 | 42 | 20 |
| | disinfecting + preserving | 0.02 | 0.05 | 22 | 17 | 15 | 6 |
| | synthetic resins + fibres | 0.73 | 7.53 | 4 | 7 | 18 | 14 |
| | bleaching + dyeing | 0.64 | 0.60 | 12 | 53 | 40 | 17 |
| | other organic compounds | 5.21 | 9.31 | 13 | 16 | 29 | 41 |
| | pharmaceutical + biotech. | 0.30 | 4.65 | 11 | 8 | 7 | 1 |
| | coal + petroleum prods. | 0.99 | 1.97 | 5 | 24 | 49 | 37 |
| Electrical/ electronic | telecommunications | 7.94 | 2.19 | 47 | 52 | 50 | 15 |
| | other elect. communicns. | 0.64 | 1.28 | 27 | 15 | 14 | 18 |
| | special radio systems | 0.38 | 0.60 | 9 | 12 | 52 | 38 |
| | image + sound equipment | 1.42 | 1.50 | 29 | 42 | 41 | 5 |
| | semiconductors | 0.02 | 1.55 | 1 | 1 | 3 | 25 |
| | office equipment + DP | 0.51 | 4.03 | 15 | 5 | 4 | 7 |
| | calculators + typewriters | 1.03 | 0.31 | 48 | 50 | 48 | 13 |
| | photographic equipment | 0.65 | 0.95 | 25 | 48 | 6 | 9 |
| | illumination devices | 2.81 | 1.52 | 18 | 29 | 55 | 50 |
| | elect. devices + systems | 11.73 | 5.65 | 37 | 41 | 45 | 39 |
| | other general elect. equip. | 8.14 | 4.27 | 45 | 33 | 38 | 31 |
| Mechanical | metallurgical processes | 1.95 | 2.20 | 26 | 36 | 19 | 22 |
| | misc. metal products | 3.37 | 2.44 | 33 | 34 | 31 | 36 |
| | metalworking equip. | 4.01 | 1.81 | 46 | 45 | 28 | 34 |
| | chemical + allied equip. | 2.90 | 3.49 | 21 | 26 | 34 | 21 |
| | building material equip. | 0.86 | 0.19 | 44 | 55 | 43 | 51 |
| | material handling equip. | 2.10 | 1.76 | 28 | 27 | 27 | 45 |
| | construction equip. | 0.03 | 0.08 | 24 | 9 | 5 | 44 |
| | mining equip. | 0.07 | 1.00 | 2 | 6 | 8 | 28 |
| | agricultural equip. | 1.22 | 0.44 | 38 | 38 | 46 | 52 |
| | food + tobacco equip. | 0.11 | 0.08 | 23 | 31 | 33 | 55 |
| | textile machy. | 6.16 | 0.83 | 50 | 54 | 53 | 53 |
| | papermaking equip. | 0.51 | 0.69 | 20 | 18 | 22 | 46 |
| | printing equip. | 1.30 | 0.32 | 53 | 46 | 37 | 32 |
| | woodworking machy. | 0.12 | 0.02 | 55 | 47 | 32 | 40 |
| | other special machy. | 2.65 | 1.67 | 39 | 32 | 25 | 48 |
| | other general ind. equip. | 8.07 | 5.11 | 34 | 39 | 36 | 33 |
| | elect. lamp manufacturing | 0.20 | 0.11 | 41 | 28 | 39 | 43 |
| | power plants | 0.41 | 0.99 | 17 | 4 | 35 | 35 |
| | other instruments | 6.26 | 7.68 | 30 | 23 | 30 | 10 |
| Transport | internal combustion | 1.05 | 1.12 | 35 | 30 | 44 | 4 |
| | motor vehicles | 0.45 | 0.51 | 31 | 25 | 20 | 30 |
| | aircraft | 0.57 | 0.39 | 36 | 10 | 51 | 42 |
| | ships + marine | 0.17 | 0.14 | 49 | 51 | 2 | 29 |
| | railway equip. | 1.15 | 0.19 | 54 | 43 | 47 | 54 |
| | other transport equip. | 1.17 | 0.51 | 51 | 44 | 24 | 26 |
| | rubber + plastic prods. | 0.67 | 1.39 | 14 | 19 | 21 | 19 |
| Other | nuclear reactors | 0 | 0.43 | - | 2 | 1 | 3 |
| | textiles + leather | 0.50 | 0.06 | 43 | 56 | 56 | 49 |
| | wood products | 0.10 | 0.13 | 40 | 21 | 13 | 27 |
| | building materials | 1.57 | 3.21 | 16 | 40 | 17 | 8 |
| | food + tobacco products | 0.18 | 0.79 | 10 | 14 | 11 | 23 |
| | other + non-industrial | 2.09 | 1.04 | 52 | 37 | 26 | 12 |
| TOTAL | | 100.00 | 100.00 | | | | |

Table 5: Top 12 fastest growing fields as identified from across all industries over the interval 1930/90, and their specific ranking in each industrial sector at 15-year intervals

| **Industry** | **Chemical** | | | | **Electrical/electronic** | | | | **Mechanical** | | | | **Transport** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 fastest growing fields 1930/90 | *30/45* | *45/60* | *60/75* | *75/90* | *30/45* | *45/60* | *60/75* | *75/90* | *30/45* | *45/60* | *60/75* | *75/90* | *30/45* | *45/60* | *60/75* | *75/90* |
| 1. Chemical proc. | 38 | 3 | 8 | 6 | 14 | 6 | 3 | 5 | 7 | 6 | 2 | 5 | 55 | 53 | 1 | 17 |
| 2. Agric. chems. | 19 | 7 | 15 | 3 | 32 | 32 | 25 | 30 | 27 | 25 | 21 | 25 | 33 | 13 | 27 | 33 |
| 3. Photog. chems. | 8 | 46 | 5 | 8 | 20 | 12 | 4 | 8 | 3 | 7 | 11 | 53 | 29 | 22 | 23 | 24 |
| 4. Cleaning agents | 3 | 52 | 55 | 11 | 22 | 13 | 14 | 44 | 11 | 44 | 14 | 35 | 14 | 30 | 17 | 10 |
| 5. Synthetics | 2 | 1 | 1 | 5 | 7 | 17 | 11 | 4 | 10 | 2 | 3 | 43 | 4 | 15 | 41 | 5 |
| 6. Pharm. + bio. | 39 | 4 | 2 | 1 | 25 | 24 | 16 | 27 | 18 | 11 | 38 | 3 | 15 | 16 | 26 | 15 |
| 7. Coal + petroleum | 1 | 55 | 56 | 55 | 30 | 42 | 36 | 22 | 20 | 24 | 33 | 40 | 47 | 40 | 16 | 25 |
| 8. Semiconductors | 28 | 26 | 22 | 32 | 12 | 2 | 2 | 21 | 35 | 21 | 19 | 36 | 31 | 12 | 4 | 41 |
| 9. Data proc. | 15 | 13 | 14 | 12 | 4 | 1 | 1 | 2 | 24 | 27 | 17 | 4 | 28 | 9 | 2 | 2 |
| 10. Plastics | 7 | 41 | 16 | 43 | 45 | 19 | 18 | 10 | 13 | 19 | 26 | 17 | 51 | 47 | 38 | 7 |
| 11. Building mats. | 5 | 49 | 3 | 4 | 17 | 28 | 15 | 7 | 4 | 49 | 1 | 1 | 12 | 49 | 22 | 3 |
| 12. Food prods. | 13 | 17 | 19 | 33 | 29 | 30 | 27 | 33 | 8 | 10 | 6 | 13 | 25 | 19 | 29 | 36 |
| *Median* | *10.5* | *21.5* | *12.5* | *9.5* | *21* | *18* | *14.5* | *15.5* | *12* | *20* | *15.5* | *21* | *28.5* | *20.5* | *22.5* | *16* |

Table 6: Median changes in rankings of relative patent stocks by broad technological area within each industrial sector, 15-year intervals

| *Industrial sector* | *Tech. areas* | *1930/45* | | *1945/60* | | *1960/75* | | *1975/90* | |
|---|---|---|---|---|---|---|---|---|---|
| | | Median/QD | Rank | Median/QD | Rank | Median/QD | Rank | Median/QD | Rank |
| Chemical | C | 36 | 5 | 46 | 5 | 38 | 4 | 13 | 1 |
| | | (40) | (5) | (46) | (5) | (45) | (5) | (39) | (5) |
| | E | 25 | 2 | 19 | 1 | 22 | 2 | 26 | 2 |
| | | (22) | (2=) | (10.5) | (2) | (16.5) | (3) | (17) | (3) |
| | M | 31 | 4 | 29 | 2 | 39 | 5 | 40 | 5 |
| | | (26) | (4) | (25.5) | (4) | (24.5) | (4) | (29) | (4) |
| | T | 27 | 3 | 35 | 3 | 31 | 3 | 27 | 3 |
| | | (12) | (1) | (7) | (1) | (8) | (1) | (8.5) | (1) |
| | O | 17.5 | 1 | 37 | 4 | 19 | 1 | 28.5 | 4 |
| | | (22) | (2=) | (15.5) | (3) | (15) | (2) | (13.5) | (2) |
| Electrical/ electronic | C | 28 | 3 | 24 | 2 | 17 | 1 | 22 | 2 |
| | | (12) | (3) | (21) | (2) | (18) | (2=) | (11) | (1) |
| | E | 11 | 1 | 22 | 1 | 51 | 5 | 14 | 1 |
| | | (29) | (5) | (49) | (5) | (47.5) | (5) | (41) | (5) |
| | M | 35 | 4 | 26 | 3 | 29 | 3 | 41 | 5 |
| | | (23) | (4) | (26) | (4) | (28) | (4) | (19.5) | (3) |
| | T | 45 | 5 | 43 | 5 | 38 | 4 | 36 | 4 |
| | | (8.5) | (1) | (22.5) | (3) | (18) | (2=) | (16) | (2) |
| | O | 27.5 | 2 | 33 | 4 | 28.5 | 2 | 26 | 3 |
| | | (11.3) | (2) | (8.25) | (1) | (10.5) | (1) | (21) | (4) |
| Mechanical | C | 18 | 1 | 24 | 2 | 25 | 2 | 33 | 4 |
| | | (13) | (1) | (27) | (4) | (22) | (2) | (15) | (1) |
| | E | 30 | 2 | 27 | 3 | 23 | 1 | 20 | 1 |
| | | (15) | (2) | (11.5) | (1) | (18.5) | (1) | (19) | (3) |
| | M | 32 | 3 | 38 | 4 | 34 | 5 | 41 | 5 |
| | | (31) | (5) | (34.5) | (5) | (34.5) | (5) | (34) | (5) |
| | T | 42 | 5 | 23 | 1 | 27 | 3 | 22 | 3 |
| | | (21) | (3) | (21) | (3) | (26.5) | (3) | (15.5) | (2) |
| | O | 35.5 | 4 | 41 | 5 | 32.5 | 4 | 21.5 | 2 |
| | | (25.5) | (4) | (15) | (2) | (32) | (4) | (22.3) | (4) |
| Transport | C | 27 | 3 | 25 | 2 | 21 | 2 | 23 | 1 |
| | | (19) | (3) | (17) | (3) | (10) | (1) | (16) | (2) |
| | E | 24 | 2 | 11 | 1 | 15 | 1 | 30 | 3 |
| | | (21) | (4) | (12.5) | (2) | (33) | (4) | (27.5) | (3) |
| | M | 32 | 4 | 34 | 4 | 37 | 4 | 35 | 5 |
| | | (29.5) | (5) | (25.5) | (5) | (21) | (3) | (29) | (4) |
| | T | 49 | 5 | 41 | 5 | 38 | 5 | 34 | 4 |
| | | (8) | (1) | (10.5) | (1) | (36.5) | (5) | (29.5) | (5) |
| | O | 22 | 1 | 31.5 | 3 | 30 | 3 | 27.5 | 2 |
| | | (18) | (2) | (21.3) | (4) | (16.3) | (2) | (15.3) | (1) |

Note: Figures are medians of the 56 technological fields for each sector, or their intra-sector ranks. Quartile deviations (Q3 - Q1) or their ranks are in parentheses.

## Appendix

Figure A1. Database Classification Scheme

*a) Classification of firms and affiliates to industrial groupings:*

**Four Broad Industrial Groupings**
**(CEMTIND)**

| **C**hemical | **E**lectrical/electronics | **M**echanical | **T**ransport |
|---|---|---|---|
| (82) | (45) | (107) | (50) |

↑______________↑_________________↑__________↑
↑

284 firms or corporate groupings

↑

875 companies or affiliates

==========================================================

*b) Classification of patent subclasses to technological fields:*

**Five Broad Technological Fields**
**(CEMTO)**

| **C**hemical | **E**lectrical/electronic | **M**echanical | **T**ransport | **O**ther |
|---|---|---|---|---|
| (57c) | (69c) | (221c) | (21c) | (31c) |
| (13s) | (11s) | (21s) | (7s) | (4s) |

↑___________↑______________↑__________↑_________↑
↑

56 technological sectors (s)

↑

399 technological classes (c)

↑

All corporate and individual patents

TableA1: Selected firms

| *Sector* | *Name (1930)* | *HQ country* | *Now* |
|---|---|---|---|
| Chemical (6) | Allied Chemical | USA | part of Honeywell International |
| | Du Pont | USA | Du Pont |
| | Standard Oil (NJ) | USA | Exxon Mobil |
| | Union Carbide | USA | Union Carbide |
| | IG Farben | Germany | Bayer, BASF, Hoechst (Aventis) |
| | Swiss IG | Switzerland | Novartis |
| Electrical/electronic (9) | AT&T | USA | AT&T |
| | Burroughs | USA | part of Unisys |
| | General Electric | USA | General Electric |
| | RCA | USA | part of Thomson Multimedia |
| | Singer | USA | broken up late 1980's |
| | Sperry | USA | Unisys |
| | Westinghouse Electric | USA | part of BNFL |
| | AEG-Telefunken | Germany | part of Siemens |
| | Siemens | Germany | Siemens |
| Mechanical (11) | Allis Chalmers | USA | broken up late 1980's |
| | American Can | USA | broken up late 1980's |
| | Bethlehem Steel | USA | Bethlehem Steel |
| | Deere | USA | Deere |
| | Eastman Kodak | USA | Eastman Kodak, Eastman Chemicals |
| | Emhart | USA | Emhart Fastening Teknologies |
| | International Harvester | USA | Navistar International |
| | US Steel | USA | part of USX Corporation |
| | Westinghouse Air Brake | USA | WABTEC |
| | Vickers | UK | part of Rolls-Royce |
| | Krupp | Germany | part of Thyssen-Krupp |
| Transport (6) | Bendix | USA | part of Honeywell International |
| | Firestone Tire & Rubber | USA | part of Bridgestone Corporation |
| | General Motors | USA | General Motors |
| | BF Goodrich | USA | BF Goodrich |
| | Goodyear Tire & Rubber | USA | Goodyear Tire & Rubber |
| | United Aircraft | USA | United Technologies |