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The evolution of technological trajectories 1890–1990

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Abstract

This paper quantitatively identifies changes in technological opportunities during the last century. US patent data classified at a very detailed level are used as the source of reference. By analysing the complexities behind the changing technological opportunities, epochs and typical trajectories are traced empirically. Furthermore, it is shown how the composition of technological opportunities has evolved across historical waves. The paper illustrates how technological evolution has become increasingly interrelated and complex and how typical trajectories of individual technologies explain technological evolution better than conventional aggregate measures. Evidence also suggests how path-dependent technological change is characterized by 'creative incremental development'. © 1998 Elsevier Science B.V.

Keywords: Evolution; History of technology; Patents; Structural change; Technological trajectories

JEL classification: O30; O31; P49

1. Introduction

It has been argued by new-institutional economists that changing technological opportunities along trajectories governed by paradigms or regimes is perhaps the most central regulating variable in society (Dosi, 1982, 1988; Freeman et al., 1982; Perez, 1983; ; Freeman and Perez, 1988).

The great bulk of work which has been published within new-institutional economics has predominately been concerned, in a theoretical fashion, with the mechanism

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or process of technological change and its implications for corporate competence, industrial and international competitiveness and economic growth. Any empirically powerful overview concerning what the technological paradigms and trajectories of technological opportunities actually looked like during the last century of technological evolution has been lagging behind theoretical contributions and individual case studies, many of which cover only relatively short periods of time. In addition, attempts to identify quantitatively and statistically the underlying technological trajectories and patterns of technological development as well as the establishment of technological paradigms have lagged behind more qualitative accounts. The general lag of quantitative methods within new-institutional economics as a whole has recently been discussed (Lind, 1993, 1996; Whalen, 1996).

However, although it is now commonly agreed among new-institutional economists that to understand the impact of technology on the dynamics of the economy is important and that theory must pay special attention to the origin and history of new technologies as technological development is accumulative, incremental and path dependent, it is mainly only among historians that a growing interest has been aroused in studying the waves of science and technology. However, due to the colossal transformation technology makes to our lives, it is important not just to recognize the enormous range of new tools and techniques, products and processes and new sciences and disciplines developed, but to grasp the underlying trends. Hence, by applying a new-institutional theoretical approach, this paper aims to identify quantitatively and statistically measure what has been termed 'changes in technological opportunities' during the last century of technological evolution (1890–1990), in order to subsequently trace empirically the evolution of technological trajectories governed by paradigms.

The research is based empirically on a US patent database. It includes all individual and corporate patents granted in the US over the period from 1890 to 1990 and is classified at a very detailed level of disaggregation.

The organization of the patent data from which the research is based will be presented first. After that, the theoretical framework in relation to relevant literature on new-institutional economics concerning the main objective of this paper will be introduced. The areas of greatest technological opportunities within different waves of technological development will then be calculated and subsequently used to extract the complexities behind the changing technological opportunities within and between broad technological groups (chemicals, electrical/electronics, mechanical, transport and non-industrial) in a historical context. The purpose of this is first to sketch technological epochs of structural changes in patenting patterns governed by the evolution of technological paradigms from 1890 to 1990. Different possible trajectories of technological development will be recognized and the broad groups' relative contribution to specific technological paths of development will be calculated after which typical technological trajectories of great importance for each broad technological group can be identified. Finally, there will be an investigation of the degree to which the composition of technological opportunities changes over time; whether it is relatively stable or tends to fluctuate across historical waves of development. This will enable an examination of the extent to which paradigms governing new technological epochs 'creatively' destroy old ones or complement and extend them.

2. The data

As stated, this paper is based on a US patent database. It has been constructed by Professor John Cantwell at the University of Reading with assistance of the US Patent and Trademark Office.

The database comprises both individual and corporate patents granted in the US from 1890 to 1990. Each patent is classified by the year in which it was granted and by the type of technological activity with which it is most associated grouped at different levels of aggregation.

Various broad categories of technological activity can be identified by allocating classes (or a subdivision of a class) to common groups of activity. As illustrated in Fig. 1, patent classes (or a subdivision of a class) have been allocated to one of 399 technological sectors, which, in turn, belong to one of 56 technological groups. To give an example concerning the allocation of two subdivisions of a patent class: patents belonging to some of the sub-classes that fall within the US patent class number 62, refrigeration, comprise a sector (or subdivision of a patent class) that has been assigned to the technological group of chemical processes (tech5), while the remaining patents that fall under the other sub-classes within refrigeration constitute a different sector which has been allocated to general electrical equipment (tech39).

Classification of US patent data

All patents: individual and corporate

↓

US Patent Office classification: collects together patents in classes according to the underlying type of technological activity. Each class (or occasionally sub-division of a class) represents a separate technological field or sector (399 in total)

↓

Technological groups (56 in total): collect together technologically related fields or sectors in technological groups

↓

Technological groups are combined in still broader groups*:
Chemicals broad technological group (57 in total)
Electrical/electronics broad technological group (69 in total)
Mechanical broad technological group (221 in total)
Transport broad technological group (21 in total)
Other (non-industrial) technological group (31 in total)

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* The inter-group distributions of technological sectors are presented in brackets.

Fig. 1. The classification scheme.

Table 1
The types of technologies that are most characteristic for the broad technological groups, which is also captured by the 56 technological groupings

Broad group	(Tech1 to Tech56)	56 technological groups
Chemicals	2	Distillation processes
	3	Inorganic chemicals
	4	Agricultural chemicals
	5	Chemical processes
	6	Photographic chemistry
	7	Cleaning agents and other compositions
	8	Disinfecting and preserving
	9	Synthetic resins and fibres
	10	Bleaching and dyeing
	11	Other organic compounds
	12	Pharmaceuticals and biotechnology
	51	Coal and petroleum products
	55	Explosive compositions and charges
Electrical/electronics	30	Mechanical calculators and typewriters
	33	Telecommunications
	34	Other electrical communication systems
	35	Special radio systems
	36	Image and sound equipment
	37	Illumination devices
	38	Electrical devices and systems
	39	Other general electrical equipment
	40	Semiconductors
	41	Office equipment and data processing systems
	52	Photographic equipment
Mechanical	1	Food and tobacco (products and processes)
	13	Metallurgical processes
	14	Miscellaneous metal products
	15	Food, drink and tobacco equipment
	16	Chemical and allied equipment
	17	Metal working equipment
	18	Paper making apparatus
	19	Building material processing equipment
	20	Assembly and material handling equipment
	21	Agricultural equipment
	22	Other construction and excavating equipment
	23	Mining equipment
	24	Electrical lamp manufacturing
	25	Textile and clothing machinery
	26	Printing and publishing machinery
	27	Woodworking tools and machinery
	28	Other specialized machinery
	29	Other general industrial equipment
	31	Power plants
	50	Non-metallic mineral products
	53	Other instruments and controls

Table 1 (*continued*)
The types of technologies that are most characteristic for the broad technological groups, which is also captured by the 56 technological groupings

Broad group	(Tech1 to Tech56)	56 technological groups
Transport	42	Internal combustion engines
	43	Motor vehicles
	44	Aircraft
	45	Ships and marine propulsion
	46	Railways and railway equipment
	47	Other transport equipment
	49	Rubber and plastic products
Non-industrial	32	Nuclear reactors
	48	Textiles, clothing and leather
	54	Wood products
	56	Other manufacturing and non-industrial

The 56 categories have been amalgamated into five broader groups of consisting of chemical, electrical/electronic, mechanical and transport technologies, plus a residual consisting of other mainly non-industrial technologies. The types of technologies that are most characteristic for the broad technological groups, which is also captured by the 56 technological groupings, are presented in Table 1.

As the system of patent classes used by the US Patent and Trademark Office changes, the US Patent and Trademark Office fortunately reclassifies all earlier patents accordingly, so the classification is historically consistent. Furthermore, although the US Patent and Trademark Office have assigned most patents to more than one technological field or class, the Office identifies the most important or primary class of every patent and in this study the primary classification was used in all cases.

Applying this classification scheme, this paper will use patent statistics to contribute to the discussion concerning determining the rates and directions of technological change in the evolution of technological activities and opportunities. In this context, patent data serves as an indicator for two related variables: (1) the total stock of accumulated technological capability at the technological sector level, derived from innovation over time; and (2) the extent of technological opportunity, reflected in the rate of growth of total stock of technological capability (i.e. the rate of technological innovation) at the technological sector level. As patent data is only a direct measure of invention, there are equally two potential difficulties with this approach in which patent data serve as a proxy measure.

2.1. *Concerning (1)*

It is argued here that patent data can be used as a proxy for accumulated technological capability at the technological sector level, derived from innovation over time and that the evolution of the structure of patenting in that way can be regarded as reflecting the underlying pattern of technological change.

For the purpose of justifying the relevance of this assumption, it is suggested that cumulative calculations (stocks) are especially appropriate when patents are used as a proxy measure for accumulated technological capability as they capture all the features of innovated new technology. It is argued here that innovated new technology is mainly the outcome of the interaction-process between scientists, inventors, engineers, innovators and entrepreneurs, learning and market diffusion. Hence, by using accumulated patent stocks this paper takes an appropriately broad view of technology, where it includes the interaction between: (i) the universal element of technology relating to information or codified knowledge (for example patents) which is potentially tradable and potentially transferable; (ii) the tacit element of technology which is context specific and tied to local technological competence or capability; and (iii) that of market diffusion. In this way, (i) may serve as a proxy for (ii) and (iii), as well as being a direct measure of itself.

Hence, cumulative stocks of patents have been calculated for technological sectors, technological groups, broader technological groups and total. Stocks were calculated using the perpetual inventory method as in vintage capital models, with an allowance for a depreciation of the separate contribution of each new item of technological knowledge over a 30 year period — the normal assumption for the average lifetime of capital, given that new technological knowledge is partly embodied in new equipment or devices. Thus, the stock in 1919 represents a weighted accumulation of patenting between 1890 and 1919, a 30 year period with weights rising on a linear scale from 1/30 in 1890 to unity (30/30) in 1919, using 'straight line depreciation'.

Although the assumption of a 30 year life is admittedly arbitrary, it must be emphasized that this is a proxy measure of the life of the underlying technological knowledge and the tangible devices with which it is associated and not a direct measure of the lifetime of the patent itself (which is shorter). However, the results would be largely unaffected if a shorter lifetime was assumed. Although patent stocks would then fluctuate more as the smoothing process associated with accumulation would be less pronounced and so the absolute values of the growth of stocks and the intercorporate dispersion of activity would be greater, the identification of the periods in which stocks grow relatively faster or slower would be largely unaffected.

The use of patent stocks is also consistent with the theoretical notion of technological accumulation (which again is analogous to capital accumulation) and which follows from the view that technological change is a cumulative, incremental and path-dependent process (Rosenberg, 1976, 1982; Nelson and Winter, 1982; Dosi, 1988; Cantwell, 1991).

Analysing stocks also helps to reduce statistical problems that might otherwise be created by small numbers of patents and by year-to-year fluctuations in patenting, problems which are more serious at more detailed levels of disaggregation and which causes only random results.

2.2. Concerning (2)

The second potential difficulty is that patent data serves as a means of identifying the extent of technological opportunity in a sector derived from the rate of growth of total stock of technological capability. It is here assumed that a fast rate of growth of patenting (i.e. a high rate of growth in patent stock) in some technological sector or class of activity represents an area of strong technological opportunity in the period in question.

For the purpose of justifying the relevance of this assumption, quantitative evidence of patent statistics as to which technological fields have enjoyed the greatest new technological opportunities in the 20th century has been married up, compared and found to be consistent with the history of technology literature which provides an alternative qualitative assessment of trends in the technological evolution over the same periods across different technological fields, as well as other case studies of technologies chosen for their particularly important contributions to development (Andersen, 1997).

Historical patent data makes such cross-checking easier than what is possible in contemporary studies of patent classes, which are currently the fastest growing, in which the assumption that these classes depict the fields of the greatest new opportunities can only be established by an evaluation based on the judgement of experts in these fields.

Another potential (and related) problem when using patent data as a proxy for an opportunity is that the value of each patent might be very heterogeneous. Some patents reflect an area of significant importance, while other patents are never used. However, the recent studies by Cantwell (1991) and Cantwell (in press) have found that the most serious drawbacks that are involved in the (inappropriate) use of patent statistics — most notably, stochastic fluctuations in variations in the importance of individual patents and in the propensity to patent across sectors and over time are substantially ameliorated over large numbers of patents. It is believed here that by working with a large number, the relative importance within the whole population of the patent data tends to follow a normal distribution. It is also argued here that the overall effect of this heterogeneity in the results is further minimized by especially working with rates of change in patent stocks rather than absolute flows which have been commonly used elsewhere. If, for example, a patent in a certain area is never used or of no importance, the accumulated patent stock within that technological field will not grow and therefore not reflect an area of great technological opportunity.

3. Theoretical framework: the 'instituted' nature of technological trajectories

Although new-institutional economics has revitalized economics and opened many new approaches to the subject, a common idea concerning the concept of 'institutions' in the institutional tradition within economic theory is that the behaviour of the evolution of societies and technology are characterized by regularities which are specific to time, place, economic sector and technological field. Thus, the behaviour of all micro units within the economy are 'instituted' (Veblen, 1898, 1919; Nelson and Winter, 1982; Hodgson, 1988; Johnson, 1992). In this context, the institutional set-up of the economy (broadly defined) guides everyday actions and routines and it may also be the guidepost for change.

The major source of inspiration in this paper is provided by the Schumpeterian evolutionary economic approach to new-institutional economics which puts a special focus on understanding the impact of technology on the dynamics of the innovating economy. From this institutional viewpoint, the economy is portrayed by processes of knowledge and technology flows and cumulative causation rather than by flows in goods and services within an equilibrium system as provided in the neo-classical school.

In Schumpeter's earlier work, he focused on the 'individual' entrepreneur as the most important agent bringing innovations to the economic system (Schumpeter, 1934), but later he revised his theoretical scheme by giving a critical role to 'collective' work in the R&D laboratories (Schumpeter, 1942). However, new-institutional economists have taken this further and argue that the economic structure and institutional set-up form the framework for a process of interactive learning which sometimes results in innovations. Some new-institutional economists in the tradition of evolutionary economics refer to 'systems of innovation' in which they point to the existence of 'collective entrepreneurship' (Lundvall, 1992), while other new-institutional economists focus on technological trajectories and paradigms as special kind of institutions (Dosi, 1982, 1988; Freeman et al., 1982; Perez, 1983; Freeman and Perez, 1988).

The latter-mentioned studies relate economic evolution to the transformations of technological paradigms by focusing exclusively on the endogenous mechanisms that continuously produce new innovations. Whereas Dosi (1982) introduced a parallel between modern philosophy of science (which suggests the existence of scientific paradigms derived mainly from Kuhn, 1962) and the evolution of technological paradigms in which he groups technological discoveries; Perez (1983), in her notion of 'techno-economic paradigms', introduced a link between cyclical theories of technological evolution and the theories of path dependency and structural and institutional changes (for an overview see Freeman, 1994).

Freeman and Perez (1988) differ from Dosi (1988) in the sense that they refer to the Schumpeterian type of *meta*-paradigm of a dominant technological regime which rules for several decades. In their framework a radical change in the whole economy is related to a generalized shift in the techno-economic paradigm, revealing an overall shift in structures at the micro level as well as the macro level throughout the economic system. Accordingly, Freeman and Perez refer to *generalized* structural changes as the hard core of long-term theorizing.

An important feature of the technological or techno-economic paradigms is that it is not that any direction of technological development can happen, as the technological evolution is instituted into certain paths of development. Technological change and progress take place along economic and technological trade-offs defined by the paradigm and evolutionary institutional economists point to the existence of technological trajectories. Some trajectories are more likely to be followed than others, as defined by the existing paradigm and accumulated socio-economic and corporate competence. Also here there has to be distinguished between those trajectories which are specific to a particular technology, product or industry and those which are of general importance (Nelson and Winter, 1977).

The emphasis in this paper will only be on inventions and innovations which have diffused and lead to generalized technological and economic changes, so this paper operates within the framework of *meta*-paradigms. It is argued here that ex post the successful areas of new technological opportunities — or perhaps more correctly, those which survived — reflect not just the technological opportunities which have governed and been governed by the paradigms, but also the areas in which society possessed socio-economic competence, as without that the paradigm would not have been unleashed. Hence, although the focus is narrowed to the technological features of the evolution of paradigms, the characteristics of technological epochs — divided by structural changes in the pattern of evolution of technological opportunities — can be regarded as a reflection of the overall features of the paradigm.

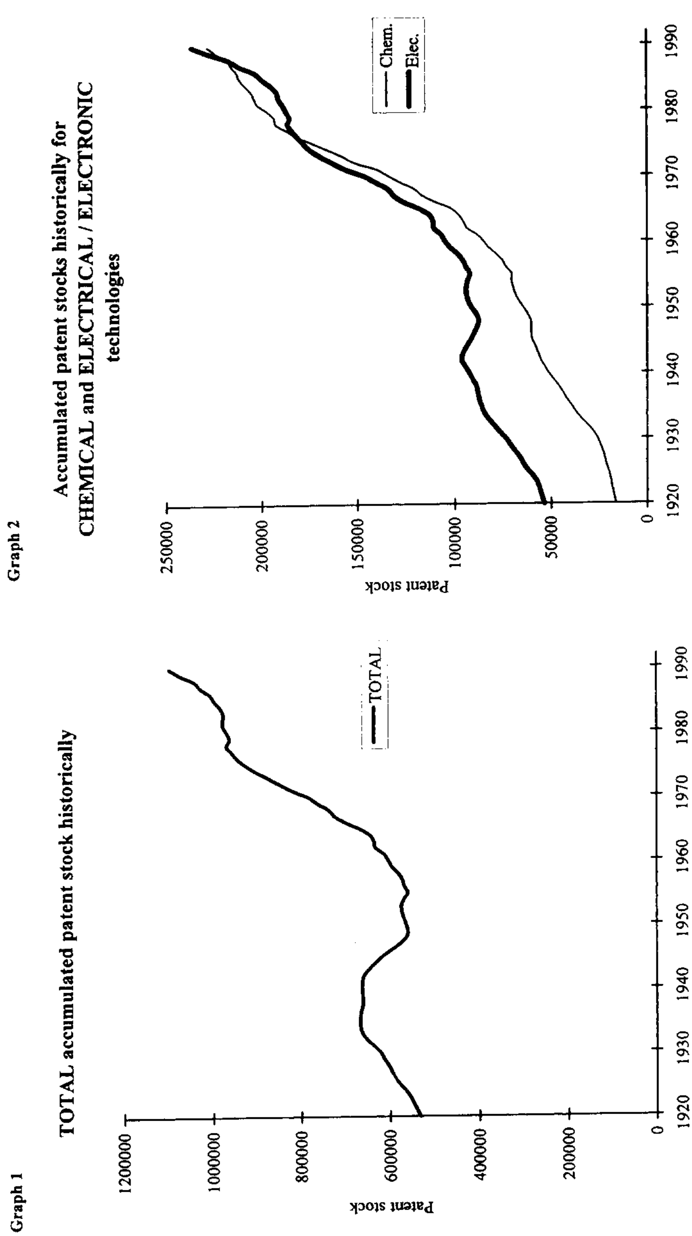
In the context of this paper, the way in which overall technological changes take place (i.e. the pattern of evolution of the technological opportunities which sets the directions of development) are referred to as technological epochs. They are, as mentioned above, separated by structural changes as well as governed by the evolution of the overall technological paradigms. The specific development paths of opportunities for selected technological sectors are defined as technological trajectories.

4. Tracing technological epochs and structural changes in patenting patterns

To obtain some ideas of the historical trends at the macro-level accumulated patent stocks for the aggregate of all patent classes and for each of the five broad technological groups are displayed in Fig. 2(a–d) in the form of graphs.

The graphs in these figures certainly suggest changes in technological opportunities over time. It can be seen that the growing opportunities in the science-based sectors (chemical and electrical/electronics) (Fig. 2(b)) have been more or less continuous in the twentieth century, except for some disruptions in the growth rates between 1940 and 1960, while the opportunities in the engineering-based sectors (mechanical and transport) (Fig. 2(b,c)) as well as the non-industrial group were weak between 1930 and 1960, over which period those broad technological groups even experienced an actual decline in accumulated patent stock. The combination of these effects suggest that the appropriate time periods into which to split the analysis are 1920–1940 (the interwar period), 1940–1960 (the war/early postwar period) and 1960–1990 (the recent period), as the general picture shows interruptions or breaks in the trends between these periods (Fig. 2(a)).

However, as modern new-institutional economists within the evolutionary tradition emphasize, the macro economy is not simply the aggregate of various micro units, but is instead regarded as a complex outcome of micro relationships or interactions; further analysis will be carried out at a more disaggregated level in order to understand the evolving structures which lies behind the shapes of the aggregate graphs.


Graph 1

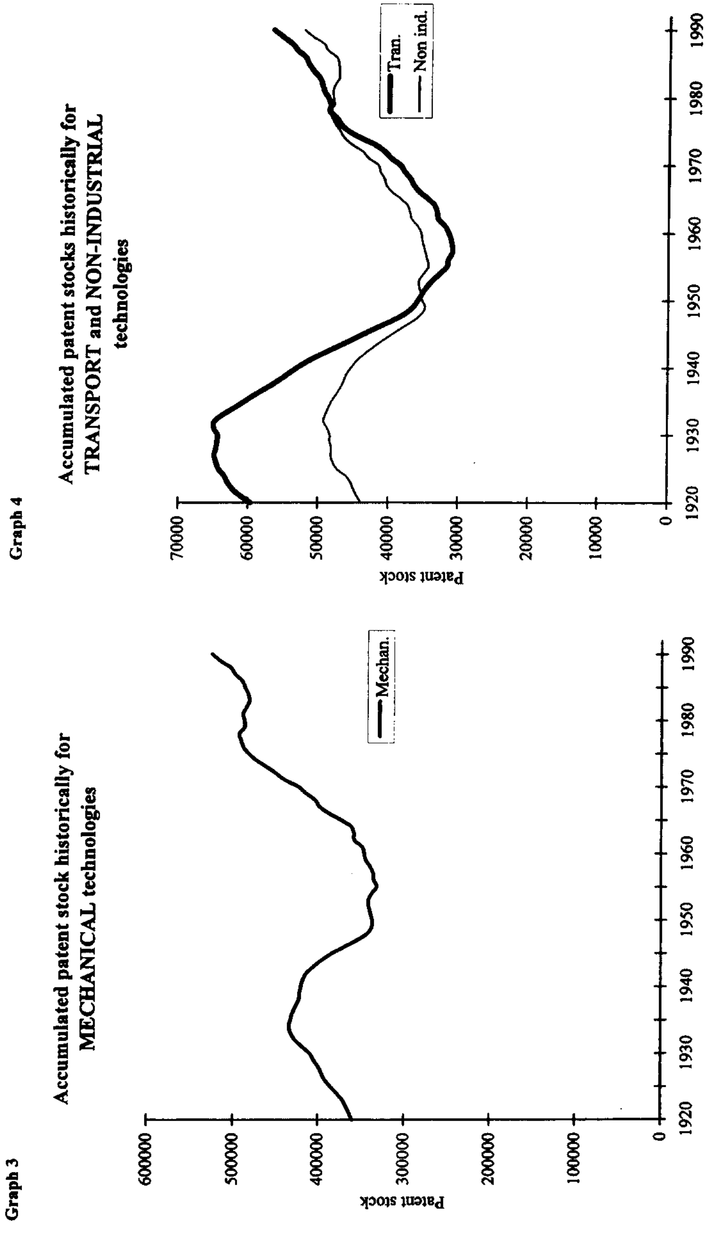
TOTAL accumulated patent stock historically

Graph 2

Accumulated patent stocks historically for CHEMICAL and ELECTRICAL / ELECTRONIC technologies

Fig. 2. Graphs showing aggregate trends for chemicals, electrical/electronics, mechanical, transport and the non-industrial group as well as the total.

When examining the complexities behind the structure of the changing technological opportunities, only patent classes which have at least 10 patents in the beginning and at the end of each of the selected periods have been included in order to avoid problems that can be created with small numbers, which can lead to very high


Graph 3

Accumulated patent stock historically for MECHANICAL technologies

Graph 4

Accumulated patent stocks historically for TRANSPORT and NON-INDUSTRIAL technologies

Fig. 2. (*continued*)

positive or negative growth rates and which represent only random statistical results. Hence, out of the 399 patent classes 369 satisfy the selection criteria, of which the chemical broad group includes 50 (down by seven), electrical/electronics accounts

Table 2
Intergroup distribution of patent classes

Technological group	Total sectors	Number of technological sectors which:			
		have ALWAYS been	DROP out	BECOME	have NEVER been
		of absolute importance during waves of technological development in the twentieth century			
Chemicals	57	50	–	3	4
Electrical/ electronics	69	57	1	8	3
Mechanical	221	213	6	1	1
Transport	21	21	–	–	–
Non-industrial	31	28	–	1	2
Total	399	369	7	13	10

for 57 (down by 12), mechanical for 213 (down by eight), transport for 21 (no change) and the non-industrial group for 28 (down by three).

As shown in Table 2, out of the 30 disqualified patent classes, some classes are disqualified because of late arrivals (new technologies coming into importance in absolute terms at some later stage of development, i.e. after 1920); others are disqualified because their technologies have dropped out of absolute importance before the last period(s) of development (i.e. before 1990). Finally, some technological sectors have never been of absolute importance across any single period of development in the 20th century.

It appears that the engineering based technologies (mechanical and transport) and non-industrial technologies were mostly already established in some form by 1920 and so had very few new technological sectors arising (two in total) at a later date — even within the mechanical group, several technological sectors (six in total) drop out of absolute importance later in the century. On the other hand, many of the science-based technologies (chemicals and electrical/electronics) only appeared to be of absolute importance during some later period of technological development in the 20th century and had several sectors (11 in total) which first gained in absolute importance after 1920, while electrical/electronics had only one technological sector dropping out of absolute importance before 1990.

The distribution of the total number of the 369 selected patent classes ranked in accordance to their technological opportunities or growth rates (high, medium or low), whether in absolute or relative terms and over the three historical periods, is presented in Table 3.

From Table 3, it can be observed that the areas of greatest technological opportunities are not concentrated within relatively few areas of related technological fields, but have been increasingly widely dispersed across the five broad technological groups. In this context, chemicals and electrical/electronics (the science-based sectors), which at the beginning of this century had a relatively high proportion of sectors ranked among the fastest growing, have generally seen a decline in their

Table 3
Intragroup distribution of five technological groups; ranked in accordance to their technological opportunities or growth rates over three historical periods

Growth rate rankings		Number of sectors			Expressed in %		
		Interwar period	War/early postwar	Recent period	Interwar period	War/early postwar	Recent period
High	Chemicals	48	40	32	96.00	80.00	64.00
	Electrical/electronics	33	31	27	57.89	54.39	47.37
	Mechanical	38	41	48	17.84	19.25	22.54
	Transport	2	1	9	9.52	4.76	42.86
	Non-industrial	2	10	7	7.14	35.71	25.00
	TOTAL	123	123	123			
Medium	Chemicals	2	9	14	4.00	18.00	28.00
	Electrical/electronics	17	16	15	29.82	28.07	26.32
	Mechanical	91	88	78	42.72	41.31	36.62
	Transport	4	4	3	19.05	19.05	14.29
	Non-industrial	9	6	13	32.14	21.43	46.43
	TOTAL	123	123	123			
Low	Chemicals	0	1	4	0.00	2.00	8.00
	Electrical/electronics	7	10	15	12.28	17.54	26.32
	Mechanical	84	84	87	39.44	39.44	40.85
	Transport	15	16	9	71.43	76.19	42.86
	Non-industrial	17	12	8	60.71	42.86	28.57
	Total	123	123	123			

share of the number of technological sectors ranked among the fastest growing, while mechanical, transport (the engineering-based sectors) and non-industrial, which at the beginning of this century had a low proportion of sectors ranked among the fastest growing, have generally seen an increase in their share of the number of the technological sectors ranked among the fastest growing. However, the greater fluctuations in the relative growth rate rankings of patenting in the transport and non-industrial spheres can be partly explained by the relatively small total number of patent classes in those groups in comparison with the other broad technological groups.

Two alternative interpretations concerning changes in the composition of the band with fastest growing technologies (or areas with highest technological opportunities) might be provided and they are classified into two models: model A and model B.

Model A argues that the technological opportunities have become less concentrated or more interrelated due to intergroup convergence in technological opportunities (see Fig. 3). The alternative explanation comes from model B, which contends that the technological opportunities have become less concentrated due to intragroup dispersion of technological opportunities (see Fig. 4). The full description of predictions based on model A and model B is described in Figs. 5 and 6.

Statistical evidence has been compiled to examine whether either model A or

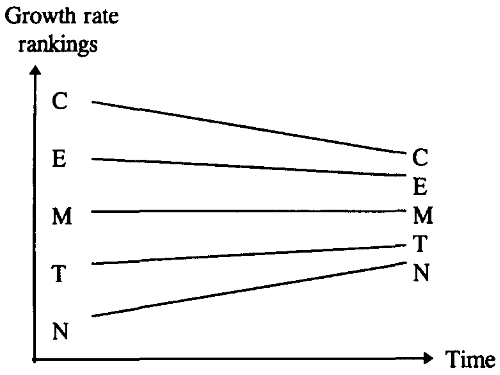


Fig. 3. Illustrative example of model A.

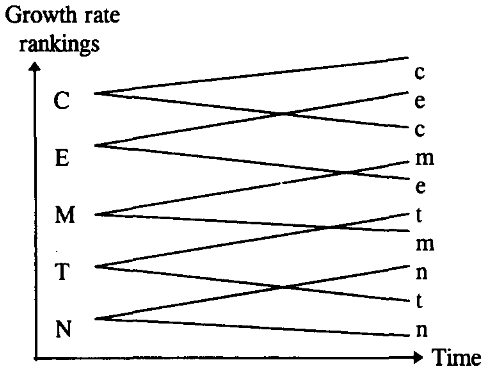


Fig. 4. Illustrative example of model B.

Cross technological group growth comparisons	Greater INTER-group dispersion between periods	Greater INTER-group convergence between periods
High growth rate ranked groups: (chemicals and electrical/electronics)	More in top ranked classes	Fewer in top ranked classes
Medium and low growth rate ranked groups: (mechanical, transport and non-industrial)	Fewer in top ranked classes	More in top ranked classes

Fig. 5. Predictions based on intergroup dispersion (or concentration) of technological opportunities.

model B (or in some cases both of them) account for the trends described. As the mean growth rates of the five technological groups vary between groups and over time (see Table 4), it is difficult to directly compare the degree of concentration and dispersion across classes within groups using the absolute measures provided by the

Cross technological sector growth comparisons →	Greater INTRA-group dispersion between periods	Greater INTRA-group convergence between periods
Cross tech. group growth comparisons		
High growth rate ranked groups: (chemicals and electrical/electronics)	Fewer in top ranked classes	More in top ranked classes
Medium and low growth rate ranked groups: (mechanical, transport and non-industrial)	More in top ranked classes	Fewer in top ranked classes

Fig. 6. Predictons based on intragroup dispersion (or concentration) of technological opportunities.

Table 4
Results concerning the relevance of model A and model B (includes average growth rates (μ), standard deviations (σ), and coefficient of variations (CVs) of five broad technological groups as well as total

		1920–1940	1940–1960	1960–1990
Average growth rates: μ (expressed in %)	$\mu_{\text{TOTAL 369}}$	132.77	15.15	88.98
	$\mu_{\text{TOTAL CEMTN}}$	163.23	22.61	103.64
	μ_C (chemicals)	364.48	104.91	200.83
	μ_E (electrical/electronics)	405.82	78.93	138.77
	μ_M (mechanical)	34.36	−13.38	55.54
	μ_T (transport)	0.65	−43.50	56.14
	μ_N (non-industrial)	10.81	−13.92	66.94
Model A. Measures INTERgroup concentration in technological growth rates: (σ) and CVs	(σ_{369})	(405.02)	(114.68)	(147.34)
	$CV_{369}=(\sigma_{369}/\mu_{\text{TOTAL 369}})\times 100\%$	305.05	756.94	165.58
	$(\sigma_{(\mu C,\mu E,\mu M,\mu T,\mu N)})$	(203.48)	(65.09)	(64.41)
	$CV_{\text{CEMTN}}=[\sigma_{(\mu C,\mu E,\mu M,\mu T,\mu N)}/\mu_{\text{TOTAL CEMTN}}]\times 100\%$	124.66	287.92	62.15
Model B. Measures INTRAgroup concentration in technological growth rates: (σ) and CVs	(σ_C)	(299.76)	(122.21)	(217.07)
	$CV_{\text{chemicals}}=(\sigma_C/\mu_C)\times 100\%$	82.24	116.49	108.09
	(σ_E)	(895.64)	(219.72)	(180.77)
	$CV_{\text{electrical/electronics}}=(\sigma_E/\sigma_E)\times 100\%$	220.70	278.36	130.26
	(σ_M)	(71.68)	(45.40)	(104.13)
	$CV_{\text{mechanical}}=(\sigma_M/\mu_M)\times 100\%$	208.60	−339.24	187.50
	(σ_T)	(56.38)	(27.29)	(89.47)
	$CV_{\text{transport}}=(\sigma_T/\mu_T)\times 100\%$	8695.8	−62.74	159.37
	(σ_N)	(63.44)	(42.23)	(113.77)
	$CV_{\text{non-industrial}}=(\sigma_N/\mu_N)\times 100\%$	586.66	−303.36	169.96

variance or the standard deviation of growth rates as these depend upon the variate scale. Therefore, this analysis needs a relative measure of the variability of the growth rates across classes in the data which for example is provided by the coefficient of variation, represented by the standard deviation divided by the mean expressed as a percentage: $CV=(\sigma/\mu)\times 100\%$. From Table 4, it can also be observed that the results concerning convergence versus divergence of growth rates in most cases varies, depending on whether the standard deviation or the coefficient of variation has been used and that the coefficient of variation is a better measure of concentration due to the great importance of the moving average growth rates over time. Moreover, other measures of concentration, such as the Herfindahl index are also better related to the CV than to the standard deviation. [For a given number of technological sectors there is a strict relationship between the coefficient of variation and the Herfindahl index; denoting the number of sectors by n and the value of the Herfindahl index by H, the relationship is $H=(CV^2+1)/n$ (Hart, 1971).]

For Model A, the CV has been calculated both: (1) using the unweighted average of all the growth rates of all the 369 individual patent classes; and (2) using the unweighted average of each of the five broad groups' unweighted averages. For model B, the CV has been calculated across individual classes' growth rates within each technological group in each period using the unweighted average of all the growth rates within each group. With respect to the calculation of the CV for model A, it appears that the results (regarding convergence *versus* divergence) are not sensitive to the different ways the average of growth rates has been calculated. The results of the average growth rates and CVs are displayed in Table 4. Only the absolute value of the CV is important (hence the positive or negative sign in front of the CV is not relevant).

By comparing the statistical results of models A and B (by viewing the changes in the CVs displayed in Table 4) with the actual general pattern of changes in the composition of the fastest growing classes (as described in Table 3) in relation to the model predictions expressed in Figs. 5 and 6, the model can be found which best explains the intergroup shifts in the rankings of patent classes.

To use the chemical broad technological group as an example, we see from Table 4 that we have intergroup divergence in technological growth rates between the interwar and the war/early postwar period as CV for total rises. In accordance with model A (which deals with intergroup issues — see Fig. 5) this means that more patent classes within chemicals would be ranked among the fastest growing. However, from Table 3 we see that the chemical technological group actually declines in share of its patent classes which is ranked among the fastest growing. Hence, model A does not explain the observed empirical evolution.

However, from Table 4 it is also observed that the CV for chemicals increases between the interwar and the war/early postwar period, reflecting intragroup divergence in growth rates. This would, in accordance with model B (which deals with intragroup issues; see Figs. 4 and 6), cause less chemical technological classes to be ranked among the fastest growing. As we see from Table 3, the broad chemical technological group actually declines in total number of classes ranked among the fastest growing, the changes in the growth rate rankings of patent classes can be

Table 5
Best model to explain the evolution of technological opportunities

Technological groups	Period: 1920–1940 to 1940–1960	Period: 1940–1960 to 1960–1990
Chemicals	B	A
Electrical/electronics	B	A
Mechanical	B	A
Transport	A and/or B	A and/or B
Non-industrial	(B)	B

concluded to be explained by model B in this case. In this way, the model which best explains the complexities behind the evolution of technological opportunities has been found for all broad technological groups and the results are listed in Table 5.

In very general terms, the results in Table 5 show that model B dominates between the interwar and the war/early postwar period, while model A dominates in the more recent period. Hence, we find two main technological epochs governing the last century. The technological epoch of intragroup divergence in the three biggest broad technological groups — chemicals, electrical/electronics and mechanical — between the two first periods may reflect the formation of specialized engineering and science-based fields and the period in which the leading sectors of each of these technological groups came to maturity and established the structure for which they are known today. For transport technologies there was instead intragroup convergence; this effect, which reduced the number of high-growing transport classes, was further reinforced by intergroup divergence, as represented by an increased CV across all technological fields and illustrated in model A. Concerning the non-industrial technological sectors, neither of the models seems to explain the technological evolution between the interwar and the war/early postwar period. However, if a conclusion has to be drawn, here too model B comes closer to explain the increase in the number of non-industrial patent classes among the faster growing. That is, while the intragroup CV_N falls, there is a tighter bunching of the span of growth rates covered by the 123 sectors in the 'medium' growth range (see Table 6). Hence, although the growth rate band among the technological sectors or classes of the non-industrial technologies decreases from −80.38% to 222.59% in the interwar period (1920–40) to −89.86% to 62.78% in the war/early postwar period (1940–60), which also is indicated by a smaller CV_N, it is still possible for this technological

Table 6
Bands for technological growth rate rankings historically

Growth rate rankings	Growth rate band (expressed in %)		
	Interwar (1920–1940)	War/early postwar (1940–1960)	Recent period (1960–1990)
High	71.94 to 4855.98	5.70 to 1436.27	88.34 to 956.51
Medium	7.02 to 71.86	−24.44 to 5.56	12.66 to 88.17
Low	−80.38 to 6.70	−89.86 to −24.73	−92.14 to 12.63

group to increase its number of patent classes ranked in the fast-growing section (although lowly ranked within that section), while dropping only by a little the number of patent classes ranked among the low growing technologies.

However, the period between the war/early postwar and up to recent times demonstrates a technological epoch of intergroup technological convergence characterizing the evolution of all broad technological groups except for the very heterogeneous non-industrial technological sectors. This reflects a new paradigm for the formation of broader technological systems as well as development of complex technologies which are offshoots of the incremental nature of technological development. These results can also be interpreted along with von Tunzelmann's notion of growing technological complexity (von Tunzelmann, 1995) and Kodama's notion of technology fusion (Kodama, 1992). It is suggestive of a historical shift towards more integrated technological systems in recent times through the fusion of diverse and formerly separate branches of technology, which explain the closing of the growth rate gap (illustrated in Tables 3 and 4) between the science-based technologies (chemicals and electrical/electronics) and the engineering-based technologies (mechanical and transport) as well as the non-industrial technologies. This evidence concerning closer connections between the principal technological families also supports the study by Patel and Pavitt (1994). In other words, technological development has become increasingly interrelated and complementary rather than independent and distinct.

That the evolution of transport technologies up to recent times is, as the only broad technological group, characterized by model B, showing dispersion of intragroup growth rates, might be related to the revival of certain transport technologies in recent times, as seen in graph 4. These results concerning structural changes in patenting patterns will now be studied in more detail with reference to specific technological sectors showing different paths of development.

5. Revealed technological trajectories

Moreover, what is interesting is not primarily or only the changing overall structure of the technological opportunities across different technological epochs, as investigated above, but an examination of what caused these changing structures. Thus, the next step of the analysis is to examine and identify how the underlying pattern of the technological opportunities of individual technological sectors have evolved over time. This is performed by deriving typical technological trajectories and selecting those of greatest historical technological importance.

Different possible trajectory types for the growth performance of patenting in each class can be identified using a general framework which have been developed for this purpose (see Fig. 7). As mentioned earlier, when investigating the structure of the changing intergroup distribution of technological opportunities (see Table 3), it sorts all eligible technological sectors or patent classes into nine groups derived by ranking them into three bands in accordance to their growth rates within each of three broad historical periods (interwar 1920–1940, war/early postwar 1940–1960

Relative growth rate ranking positions	Historical time trend		
HIGH	1	1	1
MEDIUM	2	2	2
LOW	3	3	3
	Interwar	War/early postwar	Recent period

Fig. 7. Framework for identification of technological trajectories.

and recent times 1960–1990). Also here, the growth rate ranking is performed across all the broad technological groups in order to investigate which technologies out of all sectors possible have shown the greatest opportunities historically.

This scheme can then be used as a framework to reveal many different trajectory types showing alternative paths or ways in which the 369 eligible individual technological sectors may have changed their opportunities over time. All these alternative trajectory types are traced and sorted in accordance with their initial starting point (whether they start high, medium or low growth rate ranked) and if they evolve in a linear or non-linear fashion. As will appear, there are also different types of linear and non-linear evolution paths.

Patent classes or technological sectors which follow a linear horizontal trajectory [**1** (111); **2** (222); **3** (333)] reflect those technologies whose technological opportunities remain constant historically. In addition, there are quadratic-like horizontal types of trajectories. If they are first declining, but then recovering [**6** (121, 131); **7** (232)], this seems to be technologies with dropping opportunities in the war/early postwar period. However, if they are first growing, but then falling back to their initial starting point [**12** (212); **13** (323, 313)], this indicates technologies with great opportunities in the war/early postwar period.

Finally, there are historical declining and historical growing trajectories. Declining trajectories can be linear, **5** (123), non-linear convex-like [**10** (122, 133, 132); **11** (233)], or non-linear concave-like [**16** (112, 113); **17** (223, 213)], and they all indicate historically falling opportunities. However, technological sectors performing growing trajectories, which can also be linear, **4** (321), non-linear convex-like [**8** (221, 231); **9** (332, 331)] or non-linear concave-like [**14** (211); **15** (311, 322, 312)], indicate an historical growth in new opportunities. Altogether this comprises 17 possible different trajectory types which are indicated above within parentheses.

Hence, the whole scope of the scheme is that it is believed that the total of all sectors as well as each broad technological group (chemical, electrical/electronics, mechanical, transport and non-industrial) do not follow any general trend of changing technological opportunities (i.e. is gathered in only one trajectory type), but that it is essential to use an evolutionary approach in which each technological sector's trajectory type can be exposed in order to understand the evolving structure of technological opportunities.

Given the new-institutional approach taken in this paper, it is expected that some trajectories are more likely to be followed rather than others. Thus, rather than identifying randomly and unstructured or unspecified the evolution paths of the selected 369 technological sectors or patent classes, it seems appropriate to examine to what extent a technological trend is typical for a broad technological group, which is also another way of measuring a broad groups relative contribution to specific paths of development. The analysis will also take into account that what it interesting is not only a trajectory's relative typicality for an individual group, but also the overall historical technological importance of this trajectory.

The reason for carrying such an analysis out at the group level is mainly to adjust for size, so that related technological sectors within the larger groups such as electrical/electronics and mechanical do not bias the results concerning which trajectories have been typical and dominant. This would display only electrical/electronics and mechanical major historical regimes, rather than evolving structures.

A trajectory's typicality for a technological group in comparison with those that characterize other groups and relative to other trajectory types, can then be measured by an index, which is developed for the purpose of this analysis, termed the revealed technological trajectory (*RTT*) index. It is a relative measure and it can be compared to the revealed technological advantage index (*RTA*), which is used to measure a firm's relative specialization in a technological field. (see, for example, Cantwell and Andersen, 1996). The *RTT* index will now be explained in greater detail.

The value of the *RTT* index for a particular trajectory type within a group is derived by measuring the broad technological group's share of technological sectors (or patent classes) following this particular technological trajectory type (derived from the intragroup distribution of patent classes across all alternative technological trajectory types) relative to the overall share of all patent classes in this particular trajectory type (derived from the distribution of patent classes of all technological groups across all alternative technological trajectory types).

Hence, denoting by F_{Tj} the number of technological sectors which follow technological trend T for a particular broad technological group j, the *RTT* index for each trend type in that broad technological group can then be defined as follows:

$$RTT_{Tj} = \frac{F_{Tj}/\sum_T F_{Tj}}{\sum_j F_{Tj}/\sum_T \sum_j F_{Tj}}, \qquad (1)$$

The index varies around unity such that when $RTT > 1$, the trajectory type in question is relatively typical for the technological group in question; hence, the group has a relatively massive contribution to this particular technological development paths or trajectory. However, $RTT < 1$ indicates that the trajectory in question is relatively uncommon for the technological group in question.

Thus, in order to measure the trajectory's relative typicality for each individual broad group, which is also another way of measuring the groups relative contribution to a specific technological path of development, the *RTT* index of each of the 17 technological trajectory types has been calculated for each of the five broad technological groups.

Table 7
Typical technological trajectories of great importance

Technological broad groups	Number of important trajectories where $RTT > 1$	Trajectory types (see text for Fig. 7)
Chemicals	3	1, 6, 16
Electrical/electronics	5	1, 6, 14, 16, 17
Mechanical	5	2, 3, 9, 15, 17
Transport	4	3, 4, 8, 9
Non-industrial	5	8, 9, 12, 13, 15

However, as mentioned previously, what is interesting is not only a trajectory's relative typicality for an individual group, but also the overall importance of this trajectory. Hence, only typical trajectories (cases where $RTT > 1$) which each accounts for at least 10% (or close to, due to rounding) of the technological group's patent classes of which it is typical will be considered; as a cut off point higher than this reduces significantly the number of trajectories which are typical for each broad technological group and as a cut off point on about 10% still indicates technological trajectories which are of great overall importance for the broad technological group of which it is typical.

The typical technological trajectories of great overall importance for each broad technological group (i.e. cases in which $RTT > 1$ and which have an overall technological broad group patent share of about at least 10%) are displayed in Table 7. This table shows that electrical/electronics, mechanical and non-industrial all have five different technological trajectories which are of great importance for the groups and typical relative to evolution paths in other groups, while transport has four. However, chemical technologies seem to be gathered in only three typical technological trajectories of great importance.

These findings certainly suggest that it would be an oversimplification to draw any generalized conclusions concerning typical and historical important technological trajectories at the aggregate group level, as the different technological sectors belonging to each of the technological broad groups show a quite complex intragroup pattern in their technological evolution with alternative typical technological trajectories going in totally different directions across different periods of technological development. Hence, all broad groups contribute to various alternative historical technological important paths of development. The typical trajectories of great importance for each broad technological group, as presented in Table 7, will now be explained.

Concerning chemicals, as many as 44 out of the group's 50 eligible classes (i.e. 88%) are gathered in three typical technological trajectories showing historical important paths of development. In this context, technological sectors documenting continuous opportunities throughout (trajectory 1) include the overall set of subclasses belonging to agriculture chemicals (tech4). Also the overall set of subclasses belonging to photographic chemistry (tech6) and most patent classes within synthetic resins and fibres (tech9) (including rubber, plastics and adhesives from the polymer industry), as well as most classes belonging to pharmaceuticals and biotechnology (tech12) are gathered in this trajectory of continuous opportunities throughout and so is a great part of the patent classes belonging to chemical processes (tech5) and other organic compounds (tech11). Another typical technological trajectory within chemicals indicates sectors which drop out of the high-opportunity ranking position in the war/early postwar period, but then recover in recent times (trajectory 6). This trajectory is most typical for patent classes belonging to chemistry of inorganic compounds (tech3) as well as textile chemicals including bleaching and dyeing (tech10). In fact, the overall set of subclasses within those latter mentioned groups follow this trajectory type. Finally, the last typical trajectory within chemicals indicates classes which have enjoyed great technological opportunities until 1960, but then drop out in recent times (trajectory 16). This group includes half of the subclasses within distillation processes (tech2) (the other half dropped out of high opportunities already after 1940), as well as most classes within coal and petroleum products (tech51) which especially peaked in development in the period ranging from the interwar and up to and including the early postwar period. Also about half of the sectors within organic compounds are gathered in this trajectory type.

The electrical/electronics group's five typical technological trajectories of great importance for its technological group include 36 out of the sector's total of 57 eligible patent classes (i.e. 63%) selected for this analysis. The technological sectors' contribution to the specific paths of development indicated in the five typical trajectory types are, in most cases, spread across the most of the 56 technological groupings belonging to electrical/electronics. However, by investigating the specific classes within each of the groupings in relation to the five typical trajectories and if any overall trend have to be drawn; the five typical trajectories divide between sectors which have been of continuous importance throughout the century (trajectory 1), such classes within telecommunication, office equipment and data processing systems as well as semiconductors and other sectors which were just enjoying higher or greater opportunities at some technological epoch(s) of this century. Sectors with high opportunities in the beginning of the century, or growing in opportunities up to recent period but which have since fallen in importance (trajectories 16 and 17), are typical sectors within the electrical equipment industry and technologies of electrical devices and systems. Sectors which have risen in importance (such as trajectory 14) are typically sectors within communication systems as well as other electronic devices including optics, laser and space-technology. Finally, sectors within electrical/electronics which show typical trajectories which indicate a drop in opportunities during the war/early postwar period (trajectory 6) cannot be generalized, but spread across a broad range of different technological fields. However, about half of the classes within image and sounds equipment (tech36) as well as photographic equipment (tech52) seems to follow this trajectory.

Within mechanical, only 109 out of the eligible 213 sectors in total (i.e. 51%) contribute to development paths which are typical as well as important for the broad group. Hence, this shows that we are dealing with a very technological heterogeneous sector, which is hard to group into any particular or typical paths of development. Furthermore, within mechanical, only a few of the typical technological trajectories and only some of the technological sectors within them reflect technologies which have shown high technological opportunities at any point of time in the twentieth century, although mechanical technologies as a group as a whole have been of great absolute importance in terms of accumulated technological size. Also here, as within electrical/electronics, the technological sectors' contribution to the specific paths of development indicated in five typical trajectory types are not clustered in certain broader technological categories, but spread across a range of 56 technological groupings. Sectors belonging to those few trajectories which have shown increasing technological opportunities (trajectories 9 and 15) are, for example, technologies belonging miscellaneous metal products, material handling equipment, agriculture equipment, food, drink and tobacco equipment, other general industrial equipment, power plants, etc. However, sectors which started with great opportunities, but then indicated decreasing opportunities (trajectory 17) are, for example, other specialized machinery (wrapping, brushing, coating, etc.), metal working equipment, stone working, paper making apparatus, etc.

The transport group's four typical and overall important technological trajectories presented in Table 7 include as many as 17 out of the sector's 21 eligible patent classes (81%). A high proportion of transport technologies seem to have been gathered in a trajectory with sectors continuously lowly ranked throughout this century (trajectory 3). These are particular technological sectors belonging to railway and railway equipment (tech46) or technologies concerning wheels and axles within transport equipment (tech47). However, with regard to the other typical and overall important trajectories within transport, trajectories seems to show a rising tendency and an increase in technological opportunities (trajectories 4, 8 and 9) rather than a fall. Technological fields belonging to such growing trajectories are the overall set of subclasses within internal combustion engines (tech42), the full set of classes belonging to motor vehicles (tech43), as well as a great part of the technologies within ships and marine propulsion (tech45).

Within non-industrial, 19 out of the eligible 28 sectors in total (i.e. 68%) contribute to development of notable or important trajectories which indicate typical development paths for the broad group. Among the non-industrial technologies, two out of the five typical technological trajectories indicate sectors which are increasing in technological opportunities historically (trajectories 8 and 9); while other typical trajectories show especially greater opportunities in the war/early postwar period (trajectories 12 and 13) after which they fall back to their initial starting point. However, several sectors within trajectory type 15, which show a drop in opportunities in recent times, also actually peaked among the areas of greatest opportunities in the war/early postwar period. Sectors which are rising in technological opportunities are exclusively technologies within other manufacturing and non-industrial (tech56) such as bridges, plant and animal husbandry, amusement devices and games, etc., while firearms, ammunition, explosive-charge making, ordnance as well as education and demonstration, etc. (also belonging to tech56) are among the sectors which peaked in the war/early postwar period and so did some of the technologies of knot and knot tying as well as apparel within textiles, clothing and leather (tech48).

From here, it can be concluded that typical technological trajectories governing different sub-groups or sectors within each broad technological group explain technological evolution better than aggregate technological trajectories of broad groups as a whole, as all broad groups contribute to various alternative paths of development as captured by the *RTT* index.

It is believed here that sectors within each broad technological group, which contribute to a specific path or trajectory of development which is typical and important for that group in question, may be related to families of interrelated technologies. Moreover, trajectories which indicate similar development paths, or show similar opportunities across broad groups, may even be related to broader interrelated technological families. Yet, whether technological sectors grouped together within each of the typical technological trajectories and whether typical trajectories within similar development paths across broad groups indicate interrelated technologies which could be interpreted as technological families requires a much more elaborate analysis which is outside the aim of this paper.

However, based on another study (Andersen, 1997) describing a century of technological opportunities in which the development paths of related technologies were investigated qualitatively, the results concerning such a relationship are very promising.

An example from that study will now be given in relation to the typical trajectories identified above. This example also documents how after more isolated channels of development, the technological source sectors and diffusion sectors have become less focused and more complex over time; a result or belief which was also supported quantitatively in a previous section concerning structural changes in patenting patterns.

That chemical engineering in the interwar period went through an epochal shift from coal-based to petroleum-based feedstocks pushed a whole oil-based type of a paradigm up to and including the early postwar period, based on coal and petroleum products, distillation processes and development of new and better fuels for engines (trajectory 16); as well as a new range of materials from polymers [e.g. synthetic rubber, plastics, adhesives, man-made fibres (e.g. nylon), teflon and many more] and other organic compounds which opportunities have continued up to the present (trajectory 1). Similarly, the electrification and the development of electrical devices (trajectories 16 and 17) within the electrical/electronics broad group up to and including the early postwar period have probably also been one of the most consequential technological changes. However, the more recent development of a new kind of paradigm of complex electronic based technologies (as, for example, electronic devices and related instruments including optics) (trajectory 14), as well as the continuous opportunities in technologies related to information and communication) (trajectory 1), would simply not have been possible without inventions and innovations within organic chemistry including the synthetic polymer industry. Freeman (1963) and Day (1990) argue how the polymer industry made electrical and electronic engineering manageable and how it had essential applications in developing good electric insulators and advancing electrical and electronic engineering. Likewise Chandler (1990) emphasizes how research in large companies, such as

General Electric, became in direct competition with companies from the polymer industry, such as Du Pont, from their research on insulation for wire and moulding of carbon light bulbs, etc. Other studies on polymide applications in electronics include Grupp and Schmoch (1992) and van Vianen and van Raan (1992) who studied the crossroads in polymide chemistry and electronics focusing especially on laser technology applied in medicine. This is just one example out of numerous concerning how technological families may have evolved and how technologies have become more complex.

Thus, it is found that the quantitative results presented here, concerning typical technological trajectories of areas of greatest technological opportunities for each broad technological group, are not a pure statistical or random phenomenon, but match up quite nicely with what has been suggested in the history of technology literature and other case studies on technologies chosen for their particularly important contributions to development.

6. The extent of continuity of technological opportunities or changes over time

After having investigated the overall changing intergroup growth rate ranking positions of technological opportunities and after having identified each broad groups' relative contribution to typical paths of development in which technological families may be grouped, the last step of the analysis of the evolution of technological trajectories is to examine the extent of changes in the actual composition of technological opportunities. The degree to which the technological opportunities are continuous or the extent to which they change over time will be the centre of the analysis, as well as the extent to which the opportunities change in an incremental fashion across different technological historical periods, or whether the changes are characterized by major radical disruptions in the composition of technological opportunities. Again this is better performed at the intragroup level due to the great difference in size of the broad technological groups, which would eliminate the smaller broad technological groups' overall contribution to the results.

Accordingly, this analysis concerning examining the changing composition of technological opportunities across different technological periods is performed though a statistical analysis by decomposing the changes in the pattern of intragroup growth rates across fields into a 'regression effect' and a 'mobility effect'. The statistical principle is commonly known as a 'Galtonian regression' (see also Hart, 1994; Cantwell and Andersen, 1996).

In this framework, the regression coefficient β measures the intragroup changes in the distributions of patent classes' relative growth rates over time (i.e. whether the intragroup growth rates tend to move closer to or further away from the mean). The magnitude of the regression effect is measured by $(1-\hat{\beta})$, as for $\hat{\beta}=1$ (or $1-\hat{\beta}=0$) there is on average no intragroup convergence or divergence of growth rates. The other feature arising from the regression analysis is a simple test of the extent of mobility or fluctuations in growth rates across patent classes (i.e. whether the intragroup variations in growth rates indicate patterns of stability or fluctuations in technological opportunities across fields over time). The correlation coefficient ρ is a measure of degree of mobility or fluctuations of patent classes over time. The magnitude of the mobility effect is measured by $(1-\hat{\rho})$, as for $\hat{\rho}=1$ (or $(1-\hat{\rho}=0)$ there is no mobility.

Two simple cross-section regressions of patent classes' growth rates expanding over three broad periods (from the interwar $t-2$ to the war/early postwar $t-1$; and from the war/early postwar $t-1$ to the recent period t) are carried out for each of the five broad technological groups (chemicals, electrical/electronics, mechanical, transport and non-industrial).

However, when exploring the dynamic process of cross-sectoral changes in the pattern of technological opportunities, it is found that it is better to express the growth rates in logarithmic form (since the distribution of the size and hence growth is closer to a log normal than a normal distribution):

$$\log(GT_i+1)=\log P_{i(t)}-\log P_{i(t-1)}, \tag{2}$$

where GT denotes the rate of growth and P denotes the patent stock of sector i in time t (or $t-1$). Hence, the degree of continuity of areas of greatest technological opportunities can then be statistically tested using following cross-section regressions.

Between the interwar (1920–40) and the war/early postwar period (1940–60):

$$[\log(GT+1)]_{i(t-1)}=\alpha+\beta[\log(GT+1)]_{i(t-2)}+\epsilon_{(t-1)}, \tag{3}$$

where $[\log GT+1]$ refers to the logarithm of rate of growth in patent stock i over the time period in question.

Between the war/early postwar (1940–60) and the recent period (1960–90):

$$[\log(GT+1)]_{i(t)}=\alpha+\beta[\log(GT+1)]_{i(t-1)}+\epsilon_{(t)}, \tag{4}$$

where $[\log(GT+1)]$ refers to the logarithm of rate of growth in patent stock i over the time period in question. The results are displayed in Table 8.

From Table 8, it can be observed that especially the relatively newly established science-based groups (chemicals and electrical/electronics) have each experienced a strong regression towards the mean throughout the century, reflecting an integration of historical (or relatively old) and new fields of development. Moreover, chemicals within the science-based sectors have experienced mobility or disruptions in the compositions of the intragroup growth rates, but this only in recent times. This mobility effect may suggest that the relatively newly established chemical industry is still going through some degree of 'search and selection' process of development.

Concerning the older and more mature engineering-based sectors (mechanical and transport), the regression effect has decreased significantly concerning mechanical technologies, while this effect for transport has been very low throughout the century and was not even statistically significant in the shift up to the war/early postwar period. Concerning the mobility effect, it has not been significant at all for the engineering-based sectors. These findings seem to indicate that for the older and more mature engineering-based sectors less intragroup movements and integration

Table 8
The extent of continuity in the composition of technological opportunities within broad technological groups over time; between the interwar (1920–1940) and the war/early postwar period (1940–1960): regression 1, $[\log GT+1]_{i(t-1)}=\alpha+\beta[\log GT+1]_{i(t-2)}+\epsilon_{(t-1)}$; and between the war/early postwar (1940–1960) and the recent period (1960–1990), regression 2, $[\log GT+1]_{i(t)}=\alpha+\beta[\log GT+1]_{i(t-1)}+\epsilon_{(t)}$

Technological broad group	Numbers of sectors	Period	Regression effect			Mobility effect		
			$\hat{\beta}$	$(1-\hat{\beta})$	$t_{\beta 1}$	$\hat{\rho}$	$(1-\hat{\rho})$	$t_{\beta 0}$
Chemicals	50	Regression 1	0.450	0.550	−4.632***	0.480	0.520	3.786***
	50	Regression 2	0.119	0.881	−5.371***	0.105	0.895	0.728
Electrical/ electronics	57	Regression 1	0.272	0.728	−8.581***	0.397	0.603	3.204***
	57	Regression 2	0.363	0.637	−4.263***	0.312	0.688	2.431**
Mechanical	213	Regression 1	0.298	0.702	−12.701***	0.349	0.651	5.411***
	213	Regression 2	0.637	0.353	−3.682***	0.407	0.593	6.466***
Transport	21	Regression 1	0.727	0.273	−1.343	0.634	0.366	3.572***
	21	Regression 2	0.618	0.382	−1.386*	0.457	0.543	2.241**
Non-industrial	28	Regression 1	0.506	0.494	−2.576**	0.459	0.541	2.637**
	28	Regression 2	−0.047	1.047	−4.928***	0.045	0.955	−0.220

Asterisks denote statistical significance at the 1% level***, at the 5% level**, and at the 10% level*.

of technological fields, as well as disruptions in the evolution and compositions of technological opportunities, is to be expected in general.

Concerning non-industrial technologies, the regression effect has been strong and significant only in recent times, even to the extent that formerly slower growing technologies have been overtaking the formerly faster growing. Within the non-industrial technologies, there has also been an increasing mobility effect in recent times, although not statistical significant. However, it here ought to be mentioned again that this broad technological group is a residual group not based on technological interrelateness and that this overtaking of formerly slow growing technologies may just reflect the falling back of war based technologies, some of which is included in the non-industrial group and which showed high opportunities in the war/early postwar period.

These overall results suggest that the evolution of twentieth century opportunities indicate patterns of uniform movements across different periods of technological development, rather than being marked by major disruptions and random mobility. Hence, the composition of the technological opportunities, or sectoral growth rate ranking positions, does not tend to fluctuate across different historical waves of technological development. Together with a significant regression effect (although not very strong for the more mature engineering based broad groups) which reflect that both older and newer fields of technological opportunities contribute to the development of a new technological epoch; this evidence supports the now common view of creative incremental accumulation being dominant in recent times rather than radical shifts of 'creative destruction' and that new paradigms generally do not destroy old ones, but complement and extend them (Pavitt, 1986; Patel and Pavitt, 1994). This is also consistent with the evidence provided when in an earlier section exploring the complexities behind the intergroup changes in the composition of technological opportunities.

7. Conclusion

It can be concluded that the areas of greatest technological opportunities during the century ranging from 1890 to 1990 are not strongly concentrated within relatively few areas of related technological fields, but have been increasingly widely dispersed across broad technological groups over different waves of technological development; and that the evolution of the last century's technology can be divided into two major technological epochs.

Whereas the first technological epoch extending from the opening of this century until the war/early postwar period was characterized by intragroup technological diversification and the formation of a structure of specialized engineering and science-based fields, the one that has followed through to recent time [in which the gap between the science-based (chemicals and electrical/electronics) technologies on the one hand and the engineering-based (mechanical and transport) technologies and non-industrial technologies on the other hand has been widening less quickly] is suggestive of an historical shift towards more integrated technological systems through the fusion of diverse and formerly separate branches of technology. The new paradigm governing the evolution paths of technological trajectories builds to a greater extent on intergroup complementary and interrelatedness rather than more isolated individual channels of development.

Evidence also shows how all broad technological groups' relative contribution to specific technological paths or trajectories have contributed to several alternative directions of development. This suggests that it is inappropriate to draw any general conclusions concerning the specific contribution to the technological development of selected aggregate broad technological groups. The analysis also demonstrates that typical technological trajectories of great importance for each technological group (as well as of possibly interrelated technological families)explain technological evolution better than the conventional aggregate measures which give an illusory picture.

Moreover, although evidence also suggests that the composition of technological opportunities is not stable over time, but tends to change between different historical waves of technological development, the changes generally tend to follow a uniform pattern. In such a fashion path-dependent technological change along trajectories has increasingly been channelled into wider-ranging and more complex technological systems, which are offshoots of a creative incremental technological development in a variety of areas (as opposed to creative destruction) in which new and old technological fields are integrated. This evidence proposes that new paradigms do not generally destroy old ones, but complement and extend them. Thus, this certainly supports the view that technology changes and trajectories evolve in an incremental, accumulative and path-dependent fashion.

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References

Andersen, H.B., 1997. A century of technological opportunities using patent data as a sourse of interpretation 1890–1990. In: Andersen, H.B., Technological change and the evolution of corporate innovation. PhD thesis, Department of Economics, University of Reading.

Cantwell, J.A., 1991. Historical trends in international patterns of technological innovation. In: Foreman-Peck, J. (Ed.), New Perspectives on The Late Victorian Economy: Essays in Quantitative Economic History, 1860–1914. Cambridge University Press, Cambridge, UK, pp. 37–72.

Cantwell, J., in press. The History of Technological Development in Europe and the United States. Oxford University Press, Oxford.

Cantwell, J.A., Andersen, H.B., 1996. A statistical analysis of corporate technological leadership historically. Econ. Innov. New Technol. 4 (3), 211–234.

Chandler, A.D., Jr., 1990. Scale and Scope: The Dynamics of Industrial Capitalism. Harvard University Press, Cambridge, MA.

Day, L., 1990. The chemical and allied industries. In: McNeil, I. (Ed.), An Encyclopaedia of the History of Technology. Routledge, London, pp. 186–227.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Res. Policy 11 (3), 47–162.

Dosi, G., 1988. The nature of the innovation process. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L.L.G. (Eds.), Technical Change and Economic Theory. Pinter, London, pp. 221–238.

Freeman, C., 1963. The plastics industry: a comparative study of research and innovation. Natn Inst. Econ. Rev. 26, 22–61.

Freeman, C., 1994. Critical survey. The economics of technical change. Camb. J. Econ. 18, 463–514.

Freeman, C., Clark, J., Soete, L., 1982. New Technological Systems: An Alternative Approach to The Clustering of Innovation and The Growth of Industries. Unemployment and Technical Innovation. Pinter, London, pp. 64–81.

Freeman, C., Perez, C., 1988. Structural crises of adjustment: business cycles and investment behaviour. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Ed.), Technical Change and Economic Theory. Pinter Publishers, London, pp. 38–66.

Grupp, H., Schmoch, U., 1992. At the crossroads in laser medicine and polymide chemistry: patent assessment of the expansion of knowledge. In: Grupp, H. (Ed.), Dynamics of Science-Based Innovation. Springer-Verlag, Berlin/New York, pp. 269–301.

Hart, P.E., 1971. Entropy and other measures of concentration. J. R. Stat. Soc. Ser. A 134, 73–85.

Hart, P.E., 1994. Galtonian regression across countries and the convergence of productivity. University of Reading Discussion Paper in Quantitative Economics and Computing no. 19.

Hodgson, G., 1988. Economics and Institutions, A Manifesto for a Modern Institutional Economics. Policy Press, Cambridge, UK.

Johnson, B., 1992. Institutional learning. In: Lundvall, B-Å. (Ed.), National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. Pinter, London, pp. 23–44.

Kodama, F., 1992. Technological fusion and the new R&D. Harvard Bus. Rev. 70 (4), 70–78.

Kuhn, T., 1962. The Structure of Scientific Revolutions. Chicago University Press, Chicago.

Lind, H., 1993. The myth of institutional method. J. Econ. Issues 27 (1), 1–17.

Lind, H., 1996. Reply to Whalen. J. Econ. 30 (1), 282–283.

Lundvall, B-Å. (Ed.), 1992. National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. Pinter Publishers, London.

Nelson, R.R., Winter, S., 1977. In search for a useful theory of innovation. Res. Policy 6, 36–76.

Nelson, R.R., Winter, S., 1982. An Evolutionary Theory of Economic Change. Belknap Press, Harvard University, Cambridge, MA.

Patel, P., Pavitt, K., 1994. The continuing, widespread (and neglected) importance of improvements in mechanical technologies. Res. Policy 23, 533–545.

Pavitt, K., 1986. Chips and trajectories: how does the semiconductor influence the sources and direction of technological change? In: MacLeod, R.M. (Ed.), Technology and The Human Prospect. Essays in Honour of Christopher Freeman. Pinter, London, 31–54.

Perez, C., 1983. Structural change and the assimilation of new technologies in the economic and social system. Futures 15 (5), 357–375.

Rosenberg, N., 1976. Perspectives on Technology. Cambridge University Press, Cambridge, UK.

Rosenberg, N., 1982. Inside the Black Box: Technology and Economics. Cambridge University Press, Cambridge, UK.

Schumpeter, J.A., 1934. The Theory of Economic Development: An Inquiry Into Profits, Capital, Credit, Interest and The Business Cycle. Oxford University Press, London (reprinted 1967).

Schumpeter, J.A., 1942. Capitalism, Socialism and Democracy. Routledge, London (reprinted 1994).

Veblen, T., 1898. Why is economics not an evolutionary science? Q. J. Econ. XII, 373–397.

Veblen, T., 1919. The Place of Science on Modern Civilization. Russell and Russell, NY (reprinted 1961).

van Vianen, B., van Raan, A.F.J., 1992. Knowledge expansion in applied science: a bibliometric study of laser medicine and polymide chemistry. In: Grupp, H. (Ed.), Dynamics of Science-Based Innovation. Springer-Verlag, Berlin/New York, pp. 227–267.

von Tunzelmann, N., 1995. Technology and Industrial Progress. The Foundations of Economic Growth. Edward Elgar, Aldershot, UK.

Whalen, C., 1996. A Note on The Myth of Institutional Method. J. Econ. 30 (1), 279–282.