Structural Change in Innovative Activities in Four Leading Sectors

An Interpretation of the Stylized Facts

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This paper provides a quantitative picture of structural change in innovative activities in four leading sectors – chemicals, pharmaceuticals, electronics and machinery – in Europe, United States and Japan and suggests an interpretative framework for explaining the differential rates of innovation among and within these sectors. This framework claims that an in-depth understanding of sectoral uneven innovativeness needs a bottom-up analysis of the technological, institutional and microeconomic characteristics of the different industries. The concept of sectoral system is proposed and applied for the four sectors. The conclusion of this paper is that structural change is guided by the specific coevolution of the variables of the sectoral systems: knowledge and technology, firms, networks and institutions.

CHANGEMENT STRUCTUREL DANS LES ACTIVITÉS INNOVANTES DE QUATRE SECTEURS LEADERS : UNE INTERPRÉTATION DES FAITS STYLISÉS

L'article propose une description quantitative du changement structurel dans les activités innovantes relevant de quatre secteurs leaders – chimie, pharmacie, électronique et machines-outils – en Europe, aux États-Unis et au Japon, et suggère un cadre interprétatif pour expliquer le différentiel de taux d'innovation dans et entre les secteurs. Ce cadre interprétatif soutient qu'une compréhension approfondie de l'inégale capacité innovante des secteurs requiert une analyse de type bottom-up *des caractéristiques technologiques, institutionnelles et microéconomiques des différentes industries. Le concept de système sectoriel est proposé et appliqué aux quatre secteurs. La conclusion de l'article est que le changement structurel est guidé par la co-évolution spécifique des variables des systèmes sectoriels : connaissance et technologie, firmes, réseaux et institutions.*

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INTRODUCTION

Economies are undergoing major processes of structural change in their sectors and in their innovative activities. These changes are caused by several microeconomic factors that have to be taken into account and have important implications in terms of economic growth and other economic variables like employment dynamics and trade patterns. Thus countries' differential economic growth is largely expected to be related to processes of structural change which are in turn due to sectoral differences in innovation activities.

This paper is composed by two complementary parts, one quantitative and one qualitative. In the first part we assess structural change in innovative activities measured through patents within and across four main sectors: chemicals, pharmaceuticals, electronics and machinery. We show that major structural change is present in the advanced countres. In the second part we inquire which are the main factors at the base of these differential performance in the various sectors. The main conclusion is that structural change observed in the statistics is guided by the specific coevolution of the variables that composed the specific sectoral systems and that could be grouped into knowledge and technology, firms and networks and institutions.

The paper is organized in the following way. In section 2 a broad quantitative picture of innovation and structural change in chemicals, pharmaceuticals, electronics and machinery in Europe, the United States and Japan is provided. In section 3 some major factors affecting differences in innovation and growth across these four sectors are discussed using the concept of sectoral system. In section 4 the factors affecting differences across countries in these sectors are discussed. Section 5 compares critically the results obtained in this paper with a first generation of studies concerning differential performance and built around the idea of national systems of innovation. Conclusions are drawn in Section 6.

INNOVATION AND STRUCTURAL CHANGE IN CHEMICALS, PHARMACEUTICALS, ELECTRONICS AND MACHINERY IN EUROPE, THE UNITED STATES AND JAPAN

This section provides some introductory quantitative evidence on sectoral differences in innovative and economic variables and the impact of structural changes on innovative performance at country level. We focus in particular on four sectors: chemicals, pharmaceuticals and biotech, electronics (including telecoms) and machinery (including machine tools). In this section we draw first on standard statistics on economic and research activities and second on a structural decomposition analysis using the European Patent Dataset. In the first part of the analysis we are bound to provide some evidence based on standard sectoral classifications (ISIC Rev. 3). In second part we perform a finer analysis using patent data to explore structural change within our four aggregate sectors.

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Sectoral Differences in the Rate of Innovation

In the last decade the rate growth of innovation activities has been different across sectors (OECD, 2001a, 2001b; NSB, 2000). Evidence for large industries (*e.g.* two digit ISIC Rev. 3) suggests that, in the last ten years, R&D activity in telecommunications and computers and related activities grew steadily above the average of business R&D trend. Wide differences across sectors are also observed in terms of (constant price) value added and labour productivity (OECD, 2001a and 2001b). In Europe, US and Japan labour productivity grew faster in machinery and equipment (which include computers) and telecommunications.

The dynamics of the value added in the last twenty years also displayed considerable sectoral differences. High growth is observed in the value added of relatively high tech sector. Telecom, computers, computer activities and services and then pharmaceuticals are at the top of the ranking. Machinery and transport equipment exhibit a much lower contribution to national GDP. Looking at employment dynamics the pattern is similar. With the exception of computer equipments, the sectors with more value added create also more employment with computer services and pharmaceuticals at the top.[1]

Differences in innovative activities across sectors and countries can be displayed using patent data.[2] In order to do so we use our data set of patent applications to the European Patent Office (EPO/CESPRI).[3] We start the analysis considering applicants from Germany, France, Italy, United States, Japan in our four sectors: chemicals, pharmaceuticals, electronics (including telecom) and machinery (including machine tools).[4] The time period covers from 1978 to 1998 and we calculate average values on two sub-periods, 1978-1982, 1994-1998. To address the issue of structural change we first compute the share w_k of world patent of sector k (P is the amount of patent applications to EPO and subscript j refers to countries):

$$w_k = \sum_j \mathrm{P}_{kj} / \sum_k \sum_j \mathrm{P}_{kj}$$

Secondly, we look at the rate of change of these shares: $dw_k = (w_k^t - w_k^{t-1}) / w_k^{t-1}$. Finally we compute the fraction of each country, in

1. For sectoral differences in the relationship between R&D and export shares, see Montobbio, 2003.

2. Patents have long been considered as a major data source for innovation studies. They cover wide technological areas and are comparable across countries over long time series. The serious limitations are that not all innovations are patented because not all innovations meet the patentability criteria. Moreover different means of appropriability are used in different sectors and technologies. However to our knowledge there are not systematic data on non patented inventions that could complement the patent analysis and suggest the extent to which patents really represents the wide set of innovation activities (see OECD, 1994, for an early discussion and references).

3. CESPRI/EPO data-set has 1021266 patent applications for the period 78-98. Firms that are part of business groups have been treated as individual companies. In case of co-patenting each co-patentee has been credited the patent.

4. In the Annex 3-A of the patent manual (OECD, 1994, p. 77-78) there is a re-aggregation of the original IPC classes in 30 technological areas. These 30 technological areas are aggregated in six sectors. Our sectoral classification here refers to sector 1, 3, 4 and 5 (excluding technological areas 25, 26, 27, 28).

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each sector $\left(\pi_{jk} = P_{kj} / \sum_j P_{kj}\right)$ and its change between the two sub-periods: $\Delta\pi_{jk} = \pi^t_{jk} - \pi^{t-1}_{jk}$.

The two decades that we consider display relevant structural changes. Table 1 shows the values of the sectoral shares in the two sub-periods and their rate of change in the four sectors. The increased weight over twenty years of electronics and telecommunications and the decline in chemicals and machinery is remarkable.

Table 1. *Growth of patent shares (patent applications to EPO) in the four sectors and changes in the patent shares of countries*

	Sectoral shares and change			Country shares change $(\Delta\pi_{jk})$					
	w_k^{t-1}	w_k^t	dw_k	DE	FR	UK	IT	JP	US
Electronics and telecom	18.94	25.78	0.36	– 7.20	– 3.88	– 1.61	0.86	5.92	– 0.51
Pharmaceutical and biotech	14.38	13.73	– 0.05	– 13.96	0.21	– 1.77	0.09	– 0.63	13.70
Chemicals	14.05	9.88	– 0.30	– 7.68	– 0.77	– 2.95	0.54	8.45	1.69
Machine Tools and Machinery	14.24	12.84	– 0.10	4.57	– 3.88	– 5.37	2.08	8.09	– 4.13
Others	38.40	37.77	– 0.02	– 1.27	– 2.85	– 4.13	1.35	4.45	2.99

This is associated with some country patterns: in Europe, Germany, France and UK tend to have declining shares of patents (excluding machinery in Germany and pharmaceuticals in France). Germany and Italy expand their shares in machine tools and machinery. Italy improves its patent shares also in other sectors but remains with a very low absolute level of patents in each sector. Japan improves remarkably in Electronics and Telecom Chemicals and Machinery. Finally US patent shares gains are mainly concentrated in pharmaceuticals and biotech.

This aggregate picture shows a tendency towards a decline of Europe in electronics and pharmaceutical relative to US and Japan. However there is a high heterogeneity within macro sectors and a remarkable degree of structural change also within chemicals, pharmaceuticals, electronics and telecommunications and machinery and machine tools. Moreover in Europe there are countries like Sweden and Finland that are playing a major role in innovative activities in electronics and telecom. Therefore we perform the quantitative analysis at higher level of disaggregation and expand the set of European countries. We enquire which countries are ahead driving these structural changes, which countries are able to adapt and change and finally which countries are penalised by being specialised in small technological classes with a relatively lower level of technological opportunity.

We consider 135 technological classes related to chemicals, pharmaceuticals, electronics and telecommunications and machinery and machine tools[1]. The

1. Our 135 classes cover approximately 68% of EPO. More details and an analysis of the patterns of international technological specialization can be found in Malerba Montobbio (2003).

complete list of the technological classes and the concordance with IPC classification can be found in Grupp-Munt (1995). Here patent data are reclassified in terms of economically meaningful technological classes (different from IPC) in order to assess the patterns of structural change at high level of disaggregation and the impact on countries innovative performances. Sixteen countries are now considered: United States, Japan and 14 in Europe. Again the values are averages on two sub-periods, 1978-1982, 1994-1998.

In the structural decomposition analysis the following symbols are used:

i = subscript which refer to technological classes;

j = subscript which refer to countries;

$t-1$, t = superscripts which refer to the initial sub-period – 1978-82 – and to the final sub-period – 1994-98 – of comparison, respectively;

P_{ij} = amount of country $j's$ patent applications at EPO in technological class i;

$p_{ij} = P_{ij} / \sum_j P_{ij}$ = share of world patents of country j in technological class i;

$p_j = \sum_i P_{ij} / \sum_i \sum_j P_{ij}$ = the aggregate share of world patents of country j;

$s_j = \sum_j P_{ij} / \sum_i \sum_j P_{ij}$ = share of world patent of technological class i.

The two decades that we consider display relevant structural changes. Table 1 shows the values of shares (in the technological classes) at the beginning and end of the period and their rate of change:

$$ds_i = (s_i^t - s_i^{t-1}) / s_i^{t-1}.$$

In Table 2 results are displayed excluding 50 very small classes (representing 5% of the total amount of patents in the second sub-period) and only selecting out 24 significant classes with the highest and lowest values of ds_i. In the first group there are technological classes related to pharmaceuticals, biotechnology, telecommunications, electronics (excluding cosmetics). No classes from the machinery industry are among the top twelve. Conversely traditional classes in all chemical and mechanics decrease their weight in the total patent activity. In particular the quantitatively most important are in the chemical industry (insecticides and heterocyclic compounds).

Within these sectoral patterns of structural change, variation across countries, in terms of patent shares, is observed. This disaggregated evidence adds relevant details to the general picture displayed in Table 1. For each technological class the *change* in the country j share of total patents has been calculated (see Table 2):

$$\Delta p_{ij} = p_{ij}^t - p_{ij}^{t-1}$$

Three major European countries (DE, FR, UK) experienced a decline in terms of patent share in almost all the "high growth" technological classes (with few exceptions) (the particularly bad result for Germany might be also due to insti-

Table 2. *Growth of patent shares (patent applications to EPO) in the technological classes and changes in the patent shares of countries*

	Tech. class shares and change			Country shares change (P*j*)					
	s_i^{t-1}	s_i^t	ds_i	DE	FR	UK	IT	JP	US
12 classes with the highest growth of s_i									
Compounds with nitrogen function	0.03	0.62	21.88	– 10.66	– 1.73	4.82	3.33	– 24.35	14.02
Lasers	0.15	0.55	2.56	– 5.30	0.23	0.04	– 0.39	3.10	0.63
Micro-organisms, vaccines	1.02	3.23	2.18	– 7.28	– 1.95	– 0.02	0.36	– 5.55	9.82
Other pharmaceutical products	0.27	0.72	1.63	– 15.10	– 0.50	– 8.29	0.86	5.30	18.67
Cosmetics (no soaps)	0.37	0.90	1.44	– 7.09	20.78	– 5.44	0.25	0.20	– 0.96
Telephones (no mobile phones)	2.24	5.11	1.28	– 13.43	– 10.17	– 0.01	– 0.85	8.00	5.61
Hormones and derivatives	0.26	0.56	1.16	– 21.60	– 1.98	– 4.38	1.39	3.82	21.78
Computers and equipments	1.77	3.52	0.99	– 3.96	– 1.23	– 1.12	0.06	8.98	– 6.81
Other special medicines	0.87	1.67	0.92	– 7.16	– 2.46	– 2.53	1.42	– 0.41	7.65
TV, radio, TV-cameras, video-cameras, antennas	2.25	4.05	0.80	– 13.56	– 9.91	– 1.85	0.70	13.79	1.57
Electrical diagnostic devices (no X-rays)	0.87	1.46	0.67	– 10.89	– 0.84	– 0.21	0.25	– 10.52	20.06
Photocopying machines and equipments	0.20	0.31	0.58	– 15.27	– 2.10	0.50	0.04	14.32	1.39
12 classes with the lowest growth of s_i									
Torches, furnaces	0.79	0.49	– 0.38	2.59	– 2.99	– 5.35	3.04	3.60	– 1.52
Metal-working rolling mills	0.78	0.48	– 0.39	11.38	– 3.45	– 5.14	4.74	7.89	– 5.03
Nuclear power reactors	0.49	0.29	– 0.40	– 2.51	– 23.87	– 0.18	1.56	2.30	11.22
Steam-boiler	0.43	0.25	– 0.42	4.42	– 6.07	– 4.92	3.77	9.20	– 9.13
Hydrocarbons	0.50	0.28	– 0.44	– 19.62	6.14	– 6.13	1.03	7.68	11.39
Insecticides	5.13	2.80	– 0.45	– 12.13	– 0.44	– 4.12	1.18	5.03	9.94
Additives for Mineral Oil, etc.	1.05	0.57	– 0.46	– 8.65	– 1.06	– 4.06	1.07	8.65	– 1.29
Ether, alcohol peroxide	0.92	0.49	– 0.46	– 7.87	– 0.43	– 2.03	1.66	3.11	9.49
Other Chemicals	0.70	0.37	– 0.47	– 10.59	– 0.80	– 3.58	2.60	9.67	0.56
Heterocyclic compounds	3.96	2.10	– 0.47	– 15.61	0.14	– 3.08	1.28	6.71	11.42
Carbon acid	0.92	0.39	– 0.57	– 12.54	0.16	– 1.55	– 1.72	8.48	8.21
Synthetic organic colors and varnishes	0.76	0.28	– 0.63	– 26.17	– 0.70	0.30	– 0.62	15.53	9.82

tutional factors which increased the weight of German patents to EPO during its first years). Conversely US and to some extent Japan improved their patent shares in the high opportunity technological classes. The results for the other European countries in telecommunication equipment show improvements in the patent shares of Finland (FI) and Sweden (SE). In these classes (which are the biggest in the sample) there is a sharp decline of Germany and a generalised decline for Switzerland.

Similar country patterns emerge for the declining 12 classes. Germany and Italy improved their shares in the machinery sector. Japan improved considerably its shares in almost all classes while UK has declining shares. US lost shares in important machinery classes (like valves and metal working) and gained shares in large chemical classes (like insecticides and heterocyclic Compounds).

In sum this preliminary evidence shows relevant structural changes of innovative activity between and also within the four sectors analyzed. In particular we observe an increased weight of high tech sectors like pharmaceuticals and biotechnology, telecommunications, computers and related services relatively to chemicals, machinery and many technological classes related to electronics. Evidence suggests that the underlining processes encompass both innovative activities (in terms of R&D and patents) and economic variables (like value added, employment and productivity).

The Impact of Sectoral Structures on Country Patent Shares

The "structural decomposition" methodology is now used in order to describe the different components of the country improvements or declines in terms of world patent[1] and to give a synthetic picture of the impact of structural changes on country performances outlined above.[2]

Accordingly the change of country $j's$ aggregate share of world patents can be written as:

$$\Delta p_j = p_j^t - p_j^{t-1} = \mathrm{SH}_j + \mathrm{ST}_j + \mathrm{AD}_j \tag{1}$$

$\mathrm{SH}_j = \sum_i (\Delta p_{ij} s_i^{t-1})$ measures the *technology share effect* which is the gain/loss of world shares of country *j*, assuming that the world sectoral structure of patenting activities is fixed across time. This shows country *j* innovative performance assuming out structural change and its specific position with respect to changes in technological opportunities worldwide.

$\mathrm{ST}_j = \sum_i (p_{ij}^{t-1} \Delta s_i)$ measures the *structural technology effect* which indicates what the change in the country $j's$ share of world patent would be, if its

1. We follow the contribution of Fagerberg, Sollie (1987), which develop a new version of the methodology, and Laursen (1999), which applies it for the first time to patenting activities of the OECD countries.

2. Subscript *i* still refers to the technological class (i = 1, …, 135). Structural change is evaluated at the higher level of disaggregation.

shares on individual technological classes remained constant. ST_j shows whether a country increases (decreases) its share as a consequence of a "right" ("wrong") initial technological specialization. Since p_{ij} is fixed, changes are guided by Δs_i which indicates the growth in terms of technological opportunities of technological class i at the world level.

$AD_j = \sum_i (\Delta p_{ij} \Delta s_i)$. AD_j measures to what degree country j is successful in transforming the composition of its technological activities according to structural changes in world patterns of technological opportunities. Fagerberg and Sollie (1987) shows that AD_j is directly proportional to the correlation coefficient across i between Δp_j and Δs_i. So AD_j is positive (negative) if country $j's$ share increases in those technological classes which increase (decrease) their world weight in terms of patents.

Since we are interested in understanding separately the effect of a country j increase (or decrease) in its patent share in *expanding* technological classes and the same effect in *declining* technological classes, we need to use a further decomposition of AD_j (Laursen, 1999).

$$AD_j = GR_j + SG_j \tag{2}$$

$GR_j = \sum_i \Delta p_{ij}(\Delta s_i + |\Delta s_i|)/2$ is called *technology growth adaptation* and singles out the above average expanding technological classes because the sum of Δs_i with its absolute value $|\Delta s_i|$ is zero if Δs_i is negative. Therefore GR_j is positive (negative) if Δp_{ij} is positive (negative) for these technological classes. This measures the ability of countries to enter technological classes with increasing technological opportunities.

$SG_j = \sum_i \Delta p_{ij}(\Delta s_i - |\Delta s_i|)/2$ is called *technology stagnation adaptation* and singles out technological classes which display a relative decline. This is because the difference between Δs_i and its absolute value $|\Delta s_i|$ is zero if Δs_i is positive. Therefore SG_j is positive (negative) if Δp_{ij} is negative (positive) for these technological classes. This measures the ability of countries to exit technological classes with declining technological opportunities.

Table 3 presents the results for ten countries (out of sixteen) ranked for patent share change (Δp_j). Japan and US improved their shares considerably. In Europe the highest change regards the Italian patent share. Finland, Sweden, Spain, Denmark, Netherlands, Norway and Belgium display positive signs of Δp_j. Note that highest improvement in percentage terms concerns Spain and Finland whose shares of world patent increased more than three and four folds respectively, due to the very low share they had between 1978 and 1982. Conversely Germany, UK, France, Switzerland, Austria and Luxembourg have declining shares. In percentage terms the worst performance regards UK and Switzerland, loosing around 40% of their initial patent share, followed by Germany and France with a decline of about 28%.

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Table 3. *Structural Decomposition of the change in the patent shares of countries*

	$p_j(t-1)$	$p_j(t)$	Δp_j	sh_j	st_j	ad_j	gr_j	sg_j
JP	7.75	13.40	5.65	5.17	0.73	– 0.24	0.69	– 0.93
US	19.88	23.22	3.34	1.07	2.16	0.11	0.65	– 0.53
IT	1.37	2.23	0.86	1.09	– 0.06	– 0.17	0.07	– 0.23
FI	0.16	0.91	0.76	0.57	0.01	0.18	0.24	– 0.06
SE	1.28	1.66	0.38	0.20	0.01	0.17	0.20	– 0.03
ES	0.08	0.31	0.23	0.27	– 0.01	– 0.03	0.03	– 0.07
NL	2.55	2.71	0.15	– 0.07	0.16	0.07	0.04	0.03
FR	6.81	4.94	– 1.87	– 2.00	0.51	– 0.38	– 0.59	0.22
UK	5.91	3.51	– 2.40	– 2.48	– 0.22	0.30	– 0.22	0.52
DE	17.97	12.90	– 5.08	– 4.01	– 0.74	– 0.33	– 1.37	1.05

The share effect (SH_j) is the most important in every country (with the exclusion of US and Netherlands). The absolute size of SH_j is higher than Δp_j for almost all European countries with the exception of Finland, Norway, Netherlands, Austria, Switzerland and also Germany. For Italy, Spain, Norway and Belgium, which had an overall growth in their patent share, this means that their improvements would have been higher, had technological classes grown at the same rate worldwide. For France and UK which had a decline in their country share, the absence of structural change would have further increased their decline. Conversely, without structural change, US would have only a third of the observed change in its patent share.

US and Netherlands increase their share as a consequence of a "right" initial technological specialization. In particular, in the Netherlands, the increase would have been even higher, had shares on individual technological classes remained constant. Also in France the initial level of technological specialisation has a positive impact reducing the value of its market share decrease.

Sweden and Finland have been very successful in transforming the composition of their technological activities according to structural changes in world patterns of technological opportunities. For Finland and Sweden the technology growth adaptation effect has been particularly important. The technology growth adaptation effect has also been very important in US. The sign of GR_j and SG_j in France, Germany and UK is related to the fact that these countries loose patent shares in most of the technological classes considered. However in UK the technology stagnation adaptation effect is larger in absolute value. Exit from low opportunity technological classes counterbalances its share loss. In Germany and France the negative effect of exiting from expanding technological classes is stronger so the overall adaptation effect is negative.

Summing up US and Japan have experienced relatively higher growth in terms of technological activity and (in particular US) appear to have had the "correct" sectoral distribution in the first period considered. In Europe the picture is patchier: Italy and Spain have improved their patent shares but improvements have been hindered by technological specialisation in "wrong" technological classes and difficulties to adapt. Finland, Sweden and Netherlands have grown thanks to an appropriate technological specialisation and ability to adapt and enter expanding technological fields. Large Europe economies like UK, France and Germany have lost patent shares. Germany has been heavily penalised by its technological specialisation and lack of adaptation. France has declined despite the correct specialisation and UK despite the exit from declining technological classes.[1]

DISENTANGLING THE SOURCES OF DIFFERENT INNOVATIVENESS ACROSS THE FOUR SECTORS THROUGH THE USE OF THE CONCEPT OF SECTORAL SYSTEM

The Notion of Sectoral System

What are the sources of differential innovativeness across sectors? In this paper, it is proposed that some key microeconomic, technological and institutional factors account for these differences: They can be framed into the notion of *sectoral system of innovation and production*. This notion provides a set of variables and concepts that can be used in sectoral case studies in order to provide in depth analysis of the processes of sectoral transformations in different countries.

A sectoral system is composed by three main building blocks (for a more detailed analysis, see Malerba, 2002):

a. Knowledge and technological domain;

b. Actors and networks;

c. Institutions.

a) Knowledge and technological domain. Any sector could be characterised by a specific knowledge base, technologies and inputs. In a dynamic way, the focus on knowledge and the technological domain places at the centre of analysis also the issue of sectoral *boundaries,* which usually are not fixed, but change over time. Knowledge and basic technologies constitute major constraints on the full range of diversity in the behaviour and organisation of firms active in a sectoral system. Also *links and complementarities* among artefacts and activities play a major role in defining the real boundaries of a sectoral system. These links and complementarities are first of all of the static type (as input-output links are). Then there are dynamic complementarities which take into account interdependencies and feed-backs, both at the demand and at the production levels.

1. Laursen (1999) performs a similar exercise for world patenting in US with a different sectoral disaggregation and with a different time span. He considered the period between 1965 and 1988. Despite limited comparability, results for Japan, Finland, Sweden, Spain, UK and Italy catch similar patterns. However some differences in the results are striking and deserve further inquiry. In particular his evidence on US, France and Germany is opposite. Probably there are two reasons. The choice of the patent office probably overemphasizes US decline in Laursen's sample and Germany and maybe France decline in my sample. Secondly important US has guided structural changes took places in the last twenty years in relation to ICT and biotechnology (accounted for in Table 2) that can be only partially grasped in Laursen's work.

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Dynamic complementarities among artefacts and activities are a major source of transformation and growth of sectoral systems, and may set in motion virtuous cycles of innovation and change.

b) Actors and networks. A sector is composed by heterogeneous agents that are organisations and individuals (*e.g*. consumers, entrepreneurs, scientists). Organisations may be firms (*e.g*. users, producers and input suppliers) and non-firm organisations (e.g. universities, financial institutions, government agencies, trade-unions, or technical associations), including sub-units of larger organisations (*e.g*. R-D or production departments) and groups of organisations (*e.g*. industry associations). Agents are characterised by specific learning processes, competencies, beliefs, objectives, organisational structures and behaviours. They interact through processes of communication, exchange, cooperation, competition and command. Within sectoral systems, heterogeneous agents are connected in various ways through *market and non-market relationships*.

Thus in a sectoral system perspective, innovation and production are considered processes which involve systematic interactions among a wide variety of actors for the generation and exchange of knowledge relevant to innovation and its commercialisation. Interactions include market and non-market relations that are broader that the market for technological licensing and knowledge, inter-firm alliances, and formal networks of firms. Often their outcome is not adequately captured by our existing systems of measuring economic output.

The focus on users and on their cognitive frameworks puts a different emphasis on the role of *demand*. Demand is composed by individual consumers and firms characterized by knowledge, learning processes and competencies, and is affected by social factors and institutions. Thus in a sectoral system demand is not seen as an aggregate set of similar buyers, but as composed by heterogeneous agents who interact in various ways with producers. The emergence and transformation of demand play a major role in the dynamics and evolution of sectoral systems.

The types and structures of relationships and networks differ from sectoral system to sectoral system, as a consequence of the features of the knowledge base, the relevant learning processes, the basic technologies, the characteristics of demand, the key links and the dynamic complementarities.

c) Institutions. Agents' interactions are shaped by institutions, which include norms, routines, common habits, established practices, rules, laws, standards and so on, that shape agents cognition and action. They may range from the ones that bind or impose enforcements on agents to the ones that are created by the interaction among agents (such as contracts); from more binding to less binding; from formal to informal (such as patent laws or specific regulations vs. traditions and conventions). A lot of institutions are national (such as the patent system), while others are specific to sectoral systems, such as sectoral labour markets or sector specific financial institutions.

Over time, the knowledge base of innovative activities may change in different ways, for example, evolving towards a dominant design or having a drastic change. In the first case a growth of concentration and the rise of large dominant firms may take place (Utterback, 1994). In the second case, new types of competencies may be required for innovation, with major industrial turbulence, entry of new firms and turnover in industrial leadership (Jovanovic, MacDonald, 1994; Tushman, Anderson, 1986 and Henderson, Clark, 1990). Finally, changes in demand, users and applications represent another major modification in the context in which firms operate and may favour the entry of new firms rather than the success of established ones (Christensen-Rosenbloom, 1996). Change over time results in a *coevolutionary* process of its various elements, involving knowledge, technology, actors and institutions.

National boundaries are not always the most appropriate ones for an examination of the structure, agents and dynamics of sectoral systems. Often a sectoral system is highly localised and frequently defines the specialisation of the whole local area (as in the case of machinery, some traditional industries, and even information technology). In other cases (or at the same time for specific dimensions of a sectoral system, such as for inputs or demand) the relevant geographical boundaries are global.

The notion of *sectoral system of innovation and production* complements other concepts within the *innovation system* literature (Edquist, 1997, Freeman, 1987; Nelson 1993; Lundvall 1993, Carlsson-Stankiewitz, 1995; Hughes, 1984; Callon, 1992, Andersen-Metcalfe-Tether, 2001) and draws from *evolutionary theory*, which places a key emphasis on dynamics, process and transformation. (Nelson-Winter, 1982; Dosi, 1988, 1997; Metcalfe, 1997). In both approaches learning and knowledge are key elements in the change of the economic system. In addition, for evolutionary theory the environment and conditions in which agents operate may drastically differ: major differences do exist in opportunities conditions related to science and technologies exist as well as the knowledge base underpinning innovative activities and the institutional context.

Factors Affecting Differences in Innovation Across the Four Sectors

Using the concept of sectoral system it is possible to identify some key factors that affect the differential innovativeness in the four sectors examined in Section 2. Of course, while in Section 2 the analysis was mainly quantitative and highly disaggregated for the four sectors, in this section the analysis is qualitative, based on case studies and highly aggregated. In any case, the aim of the section is to provide a thorough assessment of the main microeconomic, technological and institutional factors affecting differences in growth and innovation across sectors.

Chemicals is characterized by the continuity of large multinational firms through R-D, scale and scope and the emergence of vertical division of labour. Internal R-D has been complemented by external links and the absorption of external sources of scientific and technological knowledge. The major innovators have shown great continuity in their innovativeness due to economies of scale and scope, cumulativeness and path dependence, as well as research and commercialisation capabilities.

On the contrary, *biotechnology and pharmaceuticals* are characterized by a major role of science, networks, division of innovative labour and universities, venture capital and national health systems. Several actors are the protagonists of innovation: large firms, new biotech firms (NBF) and small firms. In this sector regulation, IPR, national health systems, and demand play a major role in the innovation process. Now, a wide variety of science and engineering fields are playing important roles in renewing the search space for this sector. New biotech firms have entered into the sector, competing as well as cooperating (or being bought up) with, the established large pharmaceutical firms. More recent changes in regulation and demand are squeezing the profitability of firms and opening up new opportunities in generic drugs.

Electronics presents a wide variety of different cases. *Telecom equipment and services* are characterised by the convergence of different technologies, demand and industries; by a key role of knowledge integration and combination; and by major production specialisation. The wide variety of different specialised and integrated actors involved in innovation, ranging from the large telecom equipment producers to the new telecom service firms is due to the process of convergence of previously separated sectors such as telecom, computers, media, and so on, and by the processes of privatization and liberalization. In this broad sector innovation is very much affected by the institutional setting and by standards. *Computer hardware* is characterized by groups of specialized firms related to different platforms, each characterized by divided technical leadership of several disintegrated firms. Innovation is decentralized, and the control over the direction by a single firm became very difficult. Recently, in computer networks, modularity and connectedness increased the role of networks of firms with local development and local feedbacks. *Software* on the contrary has a highly differentiated knowledge base, several different subsectors, firms innovative specialization, user-producer interaction, global as well as local innovation and production systems, advanced human capital mobility. In software the context of application is relevant for innovation. The role of large computer suppliers in developing integrated hardware and software systems has been displaced since the early 1980s, with the spread of networked computing, the Internet, the development of open system architectures and the growth of web-based network computing. A lot of specialised software companies innovate either in package software, or in customised software. Here the role of the university is important in the open source domain. IPR play a major role in innovation and competition. Standard setting alliances support common standards in order to facilitate the diffusion and adoption of large integrated systems.

Finally, for machinery in this paper we consider only *machine tools. Machine tools* have an application specific knowledge base; firms specialization and user-producer interaction, the extensive presence of local innovation and production systems and a key role played by in-house experienced human capital, on the shop floor level and with applied technical qualification. Products are increasingly being modularised and standardized. Suppliers of components are involved in innovation. Regional clusters are very important. Thus localised user-producer interaction, learning spillovers across producers, national differences in the structure of demand lead to international differences in the rate and direction of the new technology.

As it has been clear in the brief discussion above, the features and sources of knowledge are different from sector to sector, and show major changes. In addition, knowledge is relevant for an explanation of the rate and direction of technological change, the organization of innovative and production activities and the factors at the base of innovativeness and successful growth. However the boundaries of several sectoral systems are changing over time, as a consequence of several dynamic processes related to the transformation of knowledge as well as to the convergence in demand and the changes in the type of competition.

The changes in knowledge and learning processes discussed above imply major changes in the organisation and characteristics of R-D. A rich, multidisciplinary and multisource knowledge base and a rapid technological change implies a great heterogeneity of actors in most sectors. Demand as composed by users and by consumers is a major factor in the redefinition of the boundaries of a sectoral system, stimulus for innovation, factor shaping the organisation of innovative and production activity. In addition, the emergence of new demand or the transformation of existing demand is the major element of change in sectoral systems over time. Suppliers and users affect the boundaries of sectoral systems, by making both supply and demand an integrated part of a sectoral system and by greatly affecting sectoral linkages and interdependencies. In all sectors universities play a key role in basic research and human capital formation and in some sectors (such as biotechnology and software) also they are a source of start ups and even innovation. In software or biotechnology-pharmaceuticals new actors such as venture capital have emerged over time.

COUNTRY DIFFERENCES IN INNOVATION IN THE FOUR SECTORS USING THE CONCEPT OF SECTORAL SYSTEM

In the sectors examined above, differences in the sources of knowledge, in the types and competences of actors, in the structure and evolution of networks and in the role institutions may account for differences in patterns of innovation activities across sectors. They also account for differences across countries within the same sector (Malerba, 2004).

One major source is the difference across countries in technological and scientific research capabilities within a sector. Innovation and growth are a combination of the ability of creating new products opening up new disciplines and markets and, at the same time, integrating research, teaching and industrial needs. Importantly the construction of a solid knowledge and scientific base in specific fields has often benefited from different forms and levels of public investments in their early stages (*i.e.* pharmaceutical, biotechnology and software), above all in US. Moreover the integration between in-house research and advancements in the relative transfer sciences (chemical engineering, automation and robotics, computer sciences, biotechnology, microbiology, pharmaceutical chemistry) help firms to be ahead of their competitors product and process technologies.

Another source of difference across country refers to the ability of developing and maintaining close and continuous interactions with sophisticated users. This is particularly important in the case of machine tools and chemicals (and in some segments of software and biotechnology). In machine tools and chemicals also co-location supported the innovative performance of firms. However the mechanisms connecting demand to economic success are different according to the sector. Demand can be important in terms of level (size of the market: chemicals, pharmaceuticals, packaged software), in terms of quality (machine tools in Europe, chemical engineering in US), in terms of composition (software and

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machine tools in Europe), in terms of specific requirements (machine tools in US and Japan, chemical engineering, telecom), in terms of government share (biotech in US and telecom in US). The size of the market and its degree of integration has also been a conducive factor of US success in many sectors. Europe seems to be penalised by fragmentation in some sectors with low marginal costs (packaged software and pharmaceuticals), and increasing returns to users adoption (segments of packaged software). In these cases fragmentation of markets leads often to different monopolies or vertical integrated structures that obstruct the development of technologies (see software, biotech, chemical engineering). At the same time according to the characteristics of the industry, different markets and heterogeneous users help European firms to be ahead of their competitors thanks to their ability to create customised product and process technologies (machine tools and integrated software solutions).

Also technology and innovation policies have played an important role in affecting differences in the rate of innovative activities across countries. Agents have drawn incentives and opportunities from different types of institutional packages: IPR systems, specific norms and laws, types of standards, product approval, government support and corporate governance. Patent policies are particularly important in support of the activity of smaller technology-based firms and university licensing (particularly in biotechnology and chemicals). In the US this has created the bases for a division of labour between technology suppliers and users, and allowed the development of markets for technology. Finally standardization has affected the mobile telephone industry. In particular, European firms widely benefited from the European decision of adopting GSM technology.

A specific discussion of each sector brings additional factors into the picture (for a longer discussion, see Coriat-Malerba-Montobbio, 2004). In *chemicals* countries' innovativeness and growth is mediated by the ability of large multinational firms to perform R-D, to build efficient networks (with universities or with specialized suppliers), to expand and to adapt to the changing knowledge base. Accordingly, their location depends upon regional characteristics including local demand and technological and scientific research capabilities.

In *pharmaceuticals and biotechnology*, the main factors affecting innovation and growth are a dynamic combination of a strong science base created upon a high quality and efficient organization of research and education (for scientists, entrepreneurial scientists and managers), a strong tradition in the university-industry relationship and transfer, the presence of a market for technologies within clear institutional (patent legislation) and regulatory frameworks. The size of the domestic market, its degree of competition and integration are also important in an industry with high fixed cost in R&D. It also facilitates the creation of alliances between small and big firms and an efficient division of labour. US has been able to become leader in biotechnology at the end of the 70s and beginning of the 80s thanks to the excellence of its scientific base and to firms start-ups, a combination of university spin-off, scientists, professional managers, venture capital. Geographical proximity played a major role. It is interesting to note that in UK there are most of the necessary factors conducive to the expansion of biotechnology outlined above. Nevertheless, despite being the first to develop in Europe, UK biotechnology is stagnating and only one firm has been able to launch a therapeutic product in the market. Lack of expertise at the level of scientists, managers and also technology transfer offices in universities seem to be one of the main constraining factors.

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However, a finer level of analysis may be necessary to understand in a deeper way the sources of innovation and growth. As Casper-Kettler (2000) and Casper-Soskice (2004) show, European countries may end up innovating and growing in specific sub-sectors of biotechnology. For example Germany biotechnology firms specialize into platform technologies that are then sold to other research laboratories (for example consumable kits to rationalize common molecular biology laboratory processes). These technologies are more generic and more cumulative than the standard therapeutic products, often relate to the development of equipment for pharmaceutical firms, have library of core technologies that are then customized for specific market niches. These features fit better than the standard therapeutic products with the German institutional framework (characterized by "insider" corporate governance, internal long term relationships between firms and employees, investments in firms specific knowledge). On the other hand, firms in the United Kingdom innovate and grow in standard therapeutic products which are related to the standard products developed by the dominant American industry (Casper-Kettler, 2000; Casper-Soskice, 2004).

In *electronics,* the situation is different from industry to industry and from segment to segment. For example, in *telecommunication equipment* European performance in terms of innovation is weak. In other telecom segments like *mobile phone and some internet services* European firms are performing reasonably well. Here the good performances of some European countries are the results of specific demand conditions and of historically contingent procedures of European standard setting backed by national telecommunications providers (then public monopolies). Since a large market is created European firms can retain an advantage through learning effects and innovation on the production side. In order to do so they should have the appropriate level of skilled human resources. Relatedly, as Casper-Soskice (2004) notice, during the 1990s some of the institutional features that characterize the Swedish national framework (such as the long term relationships between firms and employees) have been modified in order to take into account the new characteristics of the innovation process in mobile phones. Ericsson recognized that wireless technologies require open standards and the full exploitation of network effects. Thus in the late 1990s, Ericsson decided to make its last system integration language open rather than proprietary, and sponsored the formation of new start ups which are spin-offs from Ericsson and which aimed to develop products compatible with Ericsson's new generation of wireless technologies. On the contrary, in *software*, differences between Europe and the US are related to the fact that European packaged software suffers primarily from the first mover effects of the US industry stemming from the personal computer revolution and the effects of network externalities in software. In US federal government, military and social security system investments played also an important role stimulating research in universities, creating infrastructures and enhancing the supply of skilled personnel. In Europe fragmented markets were a significant constraint and the industrial, university and public research systems displayed feeble support to the development of personal computer applications. Those segments that are less affected by these factors are also ones where there are closer and more important ties to local content or business practice (integrated system software and multimedia software as well as the large "hidden" sector represented by in-house development and related system integration and consulting businesses). Open source software is an emergent area of European participation and expertise, which offers considerable

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promise in revitalising European systems integration and consulting activities. Again, a finer grained analysis shows that the embedded system software market appears to show the clearest signs of a dysfunction as a sectoral system of innovation in Europe and presents the clearest case for intervention in the form of new interdisciplinary research programmes and a dialogue with industry concerning their future needs.

Finally, in machine tools linkages with research centres, producers, and users, and codified knowledge are important for innovation and the role of strategic partnership has increased. In front of the transformation of the knowledge bases and the increased level of international competition, in Europe a critical factor is the continuous upgrading of labour and engineering skills. Germany strength continues to be the integration of theory and practice, manufacturing and design. Italian firms have greatly upgraded their human capital in terms of external formal training. The increasing relevance of science and subsequent increasing distance of the R&D and design processes from the production area may threaten this strength (Wengel-Shapira, 2004). In this respect, it is interesting the double effect of niche user-supplier interaction. On the one side it helps preventing strong competition from standardized low cost general purpose technologies. This is particularly true in EU. On the other side it prevents the growth of a market leader. This is recognized as one of the major cause of the US decline in these industries. In general, increased investments in system integration, presence in emerging technologies, public-private collaboration, formal training systems, technology and market intelligence, and international partnerships and linkages are also major sources of innovation.

CONCLUSIONS

This paper has provided a quantitative analysis of innovative activities within and across four main sectors – chemicals, pharmaceuticals, electronics and machinery – and has asked which factors are at the base of the different innovative performance in these sectors. Using the notion of sectoral system of innovation, it has claimed that structural change in innovative activities is the result of the coevolution of the relevant variables that compose the specific sectoral system. Thus a micro, technological and institutional "bottom up" perspective along the dimensions of a sectoral system can be conducive to a better understanding of the observed sectoral differences in innovation and consequently in the overall performance of countries.

This implies that a view centered on a sectoral system perspective may go a long way in explaining not only the characteristics of the processes of transformation in the sectors but also the reasons of the innovative and industrial performance of countries. More in general the sectoral system tool box is intended to complement and expand the traditional notion of national system of innovation which was designed to explain the process of technological catching up and the decline of countries in the past decades.

The national innovation system literature was fostered by the concern of US going down in the technological ladder relatively to Japan and the emerging economy in East Asia. It explored the idea that technological capabilities may have an important national (or regional) dimension and that an appropriate system of institutions and organisations supporting the innovative performance of firms may be important (Freeman, 1987; Lundvall, 1992; Nelson, 1993; for a survey Montobbio, 2001). This idea of national systems of innovation was also corroborated by further empirical evidence upon the persistently uneven distribution across regions and countries of innovations.

This paper suggests that the innovativeness and growth at the country level is deeply intertwined with countries' different ability to innovate in various sectors and to foster advancements and adapt in different technologies. For example, in the last decade, we have observed a remarkable innovative and export performance of the United Stated in high technology sectors, a relative decline of Japan, Germany, France, and UK in some key sectors, and a very high rate of growth of value added, productivity, export and patent shares in the telecom sector by Finland and Sweden. According to this perspective, the growth of a national innovation system is to a large extent the result of the growth (or decline) of its main sectors. For example, in recent years the US grew in particular in high growth and high opportunity sectors, while Europe has experienced a weak ability in transforming and expanding in sectors with an increased economic and innovative weight.

This raises however a set of interesting and important issues that we want to mention here: the focus on sectors and technologies as composing the national innovation system places a lot of relevance also on the processes of major intersectoral and intra-sectoral links (both national and international), on how new technologies are adopted and diffused in established sectors and how effective is the presence of high tech in low tech production. In sum, it implicitly pays a lot of attention on the local and international interdependencies among sectors. Sectors in fact should not bee seen in isolation, but related one to the other in various ways both within the same country and at the international level.

Finally, one consequence of this reasoning is that not only institutions and organisations can no longer be considered exogenous to the agents' innovative activity but that they are often created to accommodate a specific trajectory of sectoral growth or technological specialisation. In other terms, innovative success in some countries and sectors can be result not just of the appropriate institutional package (so that the institutions of a national innovation system may have different effects on the different sectoral systems) but, rather, of the flexibility of the institutional environment to adapt to new technological challenges. Often in fact institutions are created to accommodate the expansions of specific sectors. Training systems, intellectual property rights regulations, standard setting procedures are developed under the pressure and influence of the relevant groups and industrial associations. Thus firms, sectors and institutions may grow, change or decline together.

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