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Interactions in knowledge systems: Foundations, policy implications and empirical methods

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Table of contents

1. Introduction

Recent years have seen fundamental changes in the ways we conceptualise innovation processes. The purpose of this paper is to explore one such reassessment, namely 'systems' approaches to innovation: the objective is to discuss the basis and policy implications of the approach, and then the extent to which policy-relevant empirical descriptions of systems are possible. What kinds of indicators and empirical methods can we use to characterise the profile and interactions of an innovation system?

Although this paper is aimed at operational policy tasks there is nevertheless a discussion of underlying conceptual issues. These are related to the nature and characteristics of technological knowledge. The reasons for this discussion are that, firstly, these conceptual approaches have a powerful impact on the rationale for public policy, sometimes by explicit argument and sometimes because they form the 'conventional wisdom' about policy. Secondly, they affect the development of indicators. Statistics are not neutral 'bits' of data - they always have a conceptual foundation, although these are sometimes very much in the background. This implies that statistics and indicators are conceptually specific, and therefore useful for some tasks and not for others. A particular problem in mapping systems is that for the most part we are constrained to use indicators which are derived from very different explicit or implicit concepts of innovation and knowledge.

In turn, this suggests that there are no straightforward routes to empirical system mapping: we have neither purpose-designed data sources, nor any obvious methodological approach. The challenge, therefore, is to use existing indicators and methods which give an appreciative understanding of system structures, profiles and dynamics. The good news however is that there are new data sources which permit advances in this area.

The paper therefore has the following specific objectives:

- first, to contrast the concepts of knowledge which characterise neo-classical production theory and modern innovation theory, and to clarify the implications for policy and for indicator systems
- second, to outline some key public policy tasks in a knowledge-systems approach, and some of the indicator needs which they imply
- third, to discuss the types of statistics, indicators and empirical methods which can be used in mapping 'knowledge profiles' and which are available for analysis of policy measures vis-a-vis knowledge systems.

Systems approaches to scientific and technological change are part of a wide-ranging reappraisal within the analysis of economic performance. In general, the past two decades have seen major changes in thinking about the foundations and scope of policies for innovation. These changes have been driven by persistent macroeconomic problems and instabilities since the early 1970s; by scientific and technological revolutions, which are to some extent co-evolving and producing major generic technology change; and by changes in our understanding of the nature and characteristics of innovation processes, and their economic effects.

These developments are inter-related. As early as 1980, OECD analysts were arguing that the crisis of the 1970s was both long-run and technology based, and it has since become widely accepted that structural change, changing trade shares, and inter-country growth differences have strong technology components, in two senses. First, inter-country differences in performance reflect differences in relevant science and technology resources and activities (Fagerberg 1988). Secondly, such divergences appear to reflect less tangible differences in how technological knowledge is created and distributed within particular national contexts. In particular this has taken the form of an argument to the effect the industrial success of Japan reflects a new model of knowledge-sharing and coordination processes (Freeman 1987, Fransman 1990).

These developments have been associated with a much increased volume of research, theoretical and applied, on the nature, characteristics and effects of innovation processes. Such research has been based primarily on case studies of firms and industries, although there have also been a range of statistical studies based on official data sources and innovation indicators of various types. The best overall survey of this research programme is Dosi (1988). One of the key results of such work has been a rather fundamental rejection of some of the tenets of production theory and theories of invention (within economics), and of the primary innovation model which has been used for policy analysis. These basic approaches are fundamental both to the rationale for policy, and for the relevance and practical use of different types of indicators. For that reason it is also useful to discuss some of the underlying foundations both of the neoclassical mainstream and the newer alternatives, since they give rise to quite different assessments of policy objectives and indicator needs.

2. Types of system concepts in innovation performance

Systems approaches vary in emphasis and level, but they share a common core idea. This is that the overall innovation performance of an economy depends not so much on how specific formal institutions (firms, research institutes, universities etc) perform, but on how they interact with each other as elements of a collective system of knowledge creation and use, and on their interplay with social institutions (such as values, norms, legal frameworks, and so on).

The argument of this paper is that the systems approach has significant implications for the rationale, objectives and methods of public policies for science, technology and innovation. However it is important to note that there are a number of somewhat different systems approaches available from economic and social studies of innovation. Very broadly these are of three types:

Technological system approaches: analyses of technology which conceptualise technologies not as artefacts but as integrated systems of components, and supporting managerial or social arrangements. In this work the problem of understanding technologies is has three dimensions:

- an engineering level at which techniques are inter-operative or complementary;
- a cognitive level on which technologists and engineers form a consensus on problem-solving heuristics, key lines of advance and so on; and
- a managerial and social level, at which developmental and selection decisions are made.

These approaches tend to operate either with respect to particular complex technologies, or particular industries. Examples from the history of technology might include the long-run historical work of Gille (Gille, 1978), Hughes's work on electricity production and distribution systems (Hughes, 1983), or - in economic theory - Dosi's work on technological paradigms (Dosi 1982); plus a closely relevant sociological literature (see for example, Bijker et al 1992); for a general view on technological systems, see Rosenberg (1982).

Industrial cluster approaches: these are analyses which explore the performance of industrial sectors in terms of the integration of different types of firms and industries, sometimes around key technologies, and which emphasize environmental conditions and inter-industry interactions in creating dynamic clusters or blocks of industry characterised by high growth of output, productivity and - sometimes - trade shares. The best-known example of this approach in recent years is Michael Porter's **Competitive Advantage of Nations** (Porter 1992), but this approach actually has many antecedents; in particular the work of Dahmén (1950) on 'development blocks' and Hirschman (1958) on linkage effects. Although such work is strongly systemic in character, it is not necessarily focussed on the specific dynamics of innovation and technology creation (even in Schumpeter, where the emphasis is on the effects of technological change rather than its characteristics and sources).

National systems of innovation: these are essentially analyses of innovative environments which focus on processes of learning and knowledge accumulation, particularly emphasizing institutional aspects, and various form of interaction among innovators. There is a significant literature in economic geography and regional studies on this, springing out of the work of Perroux (Perroux), and mainly focussing on factors shaping the emergence of high-technology regions. But more relevant for overall policy discussion are analyses at national level; here the work of Robert Boyer and his colleagues is particularly noteworthy (for a brief overview, see Boyer 1988). But, drawing on the work of the ‘regulation’ school associated with Boyer, and linking it with innovation theory, is more recent work on the 'national innovation systems' concept. The main work is Lundvall (1992) and Nelson (1992). In turn, related to this, is the 'knowledge systems' concept first systematically proposed in Soete and Arundel (eds) (1993), and developed in David and Foray (1994). In these approaches, economic dynamics and economic performance are primarily shaped by innovation activities, and the focus is on the processes of learning through which technologies are created and used; the argument is that learning is a collective process, shaped by formal institutions (such as universities, corporations, regulatory systems etc) and by social instititions; such knowledge-creating systems are central to economic performance issues.

These system concepts overlap, but if we are using indicators it is nevertheless necessary be clear about what type of approach we are using; technological systems approaches require significant amounts of specifically technical data, to do with product characteistics and standards, for example (see for example the various papers collected in Sigurdson 1990). This paper focusses on the concept of a knowledge system and its 'distribution power', developed by David and Foray (1994), particularly its implications for public support and management of institutions for scientific and technological learning. However although this paper will draw on various components of the David-Foray approach, it should be noted that the other forms of system theory noted above have many overlaps and complementarities. This paper attempts to explore empirical policy implications which follow from the basic elements of the systems approach, whether considered via the David-Foray approach or the related national systems concept. What is different about the David-Foray approach is that is based on an explicit taxonomy of types of knowledge, and their forms of interaction. This issue is present in the ‘national systems’ approaches (see especially Johnson 1992), though not always in an explicit form. But an approach via a more elaborated concept of ‘knowledge for innovation’ is clearly central to any system theory of innovation, and it has obvious relevance to policy-makers who are dealing primarily with knowledge-creating institutions; in addition, as I shall show below, the David and Foray approach is amenable to empirical analysis. We return to the specifics of the David and Foray approach after a discussion of technological knowledge concepts and their policy implications.

3. Foundations of the 'knowledge systems' approach to innovation policy

There is a fundamental contrast between system approaches to knowledge creation and diffusion, and the approaches which have underpinned much thinking on microeconomic policy and general economic performance.

3.1 Neo-classical production theory and its concept of technological knowledge

Insofar as innovation policies have had a theoretical rationale in the past, it derives from ideas within neo-classical production theory concerning the nature of technological knowledge; these ideas have been powerfully influential in structuring views about the appropriate scope, objectives and instruments of policy. Although neo-classical ideas have been frequently criticised in the modern innovation literature, especially where it comes to policy discussion (for example, Smith 1991, Cohendet et al 1993, Metcalfe 1994), it is worth looking the approach here, since it has important implications both the the foundations of policy, as well as for indicators and the empirical operations of policy-makers.

Neo-classical production theory is built on the idea that firms face a dual production decision. Firstly, they must decide what to produce. This decision is based on rates of return: potential product lines are known, and firms will allocate and reallocate capital among them in search of the highest returns. Then the problem is the choice of production technique: firms within an industry face a given and known array of production technologies and are assumed to have the competence to operate all available production methods. Armed with this knowledge, and with a knowledge also of present and future factor and product prices, firms can make a profit-maximising choice of technique. In this context technology is seen as knowledge, and firms are able to access knowledge in a relatively rapid and costless way. With these types of underlying assumptions, the technological dimensions of production are clearly relatively unproblematic.

The problem of technological change is also unproblematic, both with respect to adaptation to already-existing technologies, and to (exogenously-given) new technologies. This type of competitive theory rests on the ideas of rapid substitution possibilities across well-defined choice sets in production. Firms move smoothly to new production configurations in response to changed environmental conditions, adjusting their technologies (that is, adjusting the capital-labour ratio) in response to changed factor or input prices. But the environment also includes technology itself. This implies that firms are adjusting instantaneously and optimally to changes in the choice set itself, although these changes are seen as exogenous to the system; new technologies simply change the long-run equilibria of the system. In this type of approach, economic efficiency rests on flexibility, both at economy-wide level (where free entry and exit to activities are central) and at firm level (where the ability to change the technical configuration of production is central to profit maximisation). These notions have had rather powerful policy effects. Both allocative and technological efficiency rest on freeing markets, removing barriers to entry (and not being too concerned about exit), removing barriers to change within the firm, and increasing competitive pressures as a form of generating incentives to optimise.

However both these types of adjustment, and hence the policies which are built on them, rest on an implied form of technological knowledge with very particular characteristics. What exactly are the underlying assumptions about the characteristics of technological knowledge?

One of the key points about neo-classical theory it does not contain any elaborated concept of production-relevant knowledge. But of course it is possible to describe the characteristics that knowledge must possess in the neo-classical approach, even though the characteristics are implicit within the analysis. We could argue that in a neo-classical world, technological knowledge must have the following attributes in order for the production theory to hold:

- it is generic. That is to say, an item of knowledge, or a particular advance in knowledge, can be applied widely among firms and perhaps among industries.
- it is codified. Transmitability implies that knowledge is written or otherwise recorded in fairly complete usable form.
- it is costlessly accessible. On the one hand this can involve the idea that transmission costs are negligible, but it can also mean that firms do not face differential cost barriers in accessing knowledge or bringing it into production.
- it is context independent. That is, firms have equal capabilities in transforming such knowledge into production capability.

It is only with these kinds of tacit assumptions about knowledge that firms can readily make optimal profit-maximising choices. If knowledge has the above features, then the production problem of the firm is essentially a problem of calculation, rather than a problem of technological capability and organization; note also that the production decision of any firm is independent of decisions made by others; interdependence or interaction between firms is not an issue.

However if these kinds of assumptions make the acquisition and operation of technologies unproblematic within equilibrium theory, they raise acute difficulties when it comes to the development of technology, and in particular to the invention of new technological principles.

3.2 Neo-classical technological knowledge and the scope of policy

Perhaps the most influential approach to business-sector R&D, and hence to policy, derives from two classic papers by Richard Nelson and Kenneth Arrow respectively (Nelson, 1959; Arrow, 1962). Although the papers have close analytical similarities, Nelson’s deals with basic science, while Arrow’s is much more an analysis of knowledge creation in the business firm in a neo-classical framework.

Arrow begins by identifying technology with knowledge: technology in the most general sense is "know-how", and therefore the process of invention "is interpreted broadly as the production of knowledge". The question then is, what are the technical and economic characteristics of knowledge, and how do these characteristics affect the amount of new productive knowledge which firms might seek to produce?

The first problem is that of uncertainty, which in this case means that knowledge outputs are not predictable from inputs: producers must commit resources to a knowledge production process without knowing the results with any accuracy. Arrow's first point is that although market economies have a number of mechanisms for sharing risks - such as insurance, contingent markets, or equities - these rarely apply to research activities. Insurance, for example, would be impractical because it would weaken incentives to succeed; only the existence of large companies, with sizeable portfolios of relatively small projects, resolves this problem (because the companies act, in effect, as their own insurance bodies).

Then there is the problem of appropriability: it is difficult or even impossible to create a market for knowledge once it is produced, so it is difficult for producers of knowledge to appropriate the benefits which flow from it. Firstly, "there is a fundamental paradox in the determination of demand for information; its value for the purchaser is not known until he has the information, but then he has in effect acquired it without cost." Secondly, any purchaser of the knowledge can in effect destroy the market, since he can reproduce the knowledge at very low, perhaps even zero, cost. If producers cannot appropriate the benefits of knowledge, then they have no incentive to produce it, and market economies will therefore underproduce which would be socially beneficial if it were produced.

A final characteristic of technological information is indivisibility. That is, the underlying knowledge must exist on a certain minimum scale before any production at all can take place, and this necessary minimum is independent of the rate of production. A familiar example of such indivisibility would be a railway, which must be constructed in its entirety before any trains can use it; and it must be constructed whether it is used by one train per day or fifty. The latter point means that there are scale economies in the use of indivisible capital goods, and this applies to technological information.

These problems of risk, indivisibility and inappropriability all suggest that market economies will systematically underinvest in R&D, and this will, argues Arrow, "lead to the conclusion that for optimal allocation to invention it would be necessary for the government or some other agency not governed by profit-and-loss criteria to finance research and invention".

But what kinds of knowledge really have the characteristics which I have sketched, and which appear to be central to the Arrow analysis? The first two characteristics clearly apply to the knowledge which results from fundamental scientific research; indeed the other classic statement of the externality problem, Nelson's 1959 paper, speaks specifically of basic science. Implicit in the Arrow approach is the idea that technological knowledge is the same kind of knowledge as basic science, indeed perhaps that it is a form of applied science.

This 'market failure' approach to knowledge production leads to a relatively simple set of policy proposals. In this set-up the basic policy task is to encourage discovery-oriented activities, and then to protect the use of the results. The problems of risk and indivisibility lead to straightforward under-provision of knowledge, and suggest that the public sector should either produce knowledge directly, or provide subsidies to knowledge-producing institutions. The appropriability problem implies the existence of a major positive externality, and suggests policies either of subsidy, or the creation of property rights (via patents or other intellectual property protection). The basic problem with the approach is that it does not give any secure guide to how to identify areas of market failure, or the appropriate levels of public support which might follow from it. There appears to be a rationale for public provision, but where, and how much? (Metcalfe, 1994)

3.3 The 'linear model' in research policy

It is worth noticing that this type of approach to innovation policy accords very well with what is sometimes called the 'linear model' of innovation. This is the view that the process of innovation is essentially a process of discovery, in which new knowledge is transformed into new products via a set of fixed (linear) sequence of phases. There is some debate about whether the term 'linear model' is really appropriate for characterising S&T policies within OECD countries over the long term, but we can outline the broad characteristics of a 'linear' approach, and this accords with many ideas and practices in post-war researhc policy. These characteristics are:

- first, the technological capabilities of a society are essentially defined by the knowledge frontier; hence, technological advance depends on expansion of the frontier by a knowledge creation process based on discovery.
- second, the knowledge which is relevant for industrial production is defined by principles which are essentially scientific, and which have in some sense been transferred, translated, or concretised from a more abstract realm.
- third, the 'translation' process is basically sequential; there are temporally and institutionally discrete phases in the translation process, and these have to occur in sequence.
- fourth, the approach is technocratic, in the sense that it views technological change broadly in terms of engineering development processes and hardware creation.

The most powerful element of this approach is the idea that innovation is based on discovery processes within science. If this is true, then clearly policy-makers have to focus on the discovery phase and its characteristics. This 'scientific discovery' model of innovation, which was implicit in Arrow's work, leads fairly directly to policies of block funding for universities, R&D subsidies, tax credits for R&D etc: the main instruments of post-war science and technology policy in the OECD area, in fact. Policies are not, of course, developed simply out of some kind of theoretical rationale, but we ought to note that what has here been called the 'linear model' approach accords well with the notions of technological knowledge and discovery which are implicit in the neoclassical framework outlined above. These linear notions remain powerfully present in policy thinking, even in the new innovatory context. For example the recent OECD TEP report contains the the notion of 'transfer sciences':

> Once industrial society's need for basic science has been reasserted, attention must be given to the disciplines which can bridge the gap between the type of

> knowledge produced by basic science and the type of knowledge needed by firms or government agencies in day-to-day activities ... The notion of transfer sciences approaches the ‘bridging’ issue in a systematic way, and involves a distinction between two types of sciences: ‘pure sciences’ and ‘transfer sciences’ ... transfer sciences play an essential role in providing an interface between the world of ‘pure science’ and the world of industry (OECD, 1992a, pp.35-37)

The presence of this type of linear, discovery-based view in the TEP report is in a way remarkable, since TEP was essentially an attempt to think explicitly about the implications of modern research on innovation processes. If that research has any generally accepted conclusions, they would have to include the idea that technological knowledge is quite distinct from scientific knowledge, and by no means derived from it. And industrial R&D is not seen as a prior act of discovery on which innovation is dependent; it tends to be seen as a process ancillary to innovation, something which firms do when they cannot solve problems with the resources of existing knowledge-bases.

Recent theory and applied research suggests that the knowledge characteristics described above are not a good guide to the nature of technological knowledge, and must therefore have limitations as a guide to the rationale and content of S&T policies. What are the alternative views, and what are their implications?

3.4 Technological knowledge in modern innovation theory

Modern innovation theory tends to emphasize quite different aspects of technological knowledge, and hence provides a different angle on the question of technological knowledge. There is no single source for this new view of technological knowledge, and the outline which follows draws on a wide range of sources.

Clearly all firms operate with some kind of technological knowledge base. However this is not a unitary knowledge base, and it seems reasonable to distinguish between three areas of production-relevant knowledge, with different levels of specificity. This kind of differentiation in fact goes back quite a long way in economics, but has been significantly developed in recent years (for an early account, see e.g. Salter, 1969, pp.13-16).

First, there is the general scientific knowledge base. This is itself highly differentiated internally and of widely varying relevance for industrial production; but some fields - such as molecular biology, solid-state physics, genetics or inorganic chemistry - have close connections with major industrial sectors. Although it is important not to overemphasize the role of scientific knowledge in modern industrial development, or to presume that there is a one-way connection between science and technology, the connections of course exist and are very important. In large part this is because organised science does not evolve simply according to some internal dynamic, but is in fact shaped by policy or funding decisions which usually have economic, industrial or military objectives.

Secondly there are knowledge-bases at the level of the industry or product-field. At this level, modern innovation analysis emphasies the fact that industries often share particular scientific and technological parameters; there are shared intellectual understandings concerning the technical functions, performance characteristics, use of materials and so on of products. Richard Nelson calls this the "generic" level of a technology:

> On the one hand a technology consists of a body of knowledge, which I shall call generic, in the form of a number of generalizations about how things work, key variables influencing performance, the nature of the currently binding constraints and approaches to pushing these back, widely applicable problem-solving heuristics, etc. I have called this the "logy" of technology ... Generic knowledge tends to be codified in applied scientific fields like electrical engineering, or materials science, or pharmacology, which are "about" technology (Nelson, 1987, pp. 75-76)

This notion tends also to underpin the important system concepts of "technological paradigm" or "technological regime": generic knowledge bases are highly structured, and tend to evolve along structured trajectories (Dosi, 1982). This part of the industrial knowledge base is public (not in the sense that it is produced by the public sector, but public in the sense that it is accessible knowledge which in principle available to all firms): it is a body of knowledge and practice which shapes the performance of all firms in an industry. Of course this knowledge base does not exist in a vacuum. It is developed, maintained and disseminated by institutions of various kinds, and it requires resources (often on a large scale). Gregory Tassey has defined the combination of knowledge and institutional base as the "technology infrastructure", in the following way:

> The *technology infrastructure* consists of science, engineering and technological knowledge available to private industry. Such knowledge can be embodied in human, institutional or facility forms. More specifically, technology infrastructure includes generic technologies, infratechnologies, technical information, and research and test facilities, as well as less technically-explicit areas including information relevant for strategic planning and market development, forums for for joint industry-government planning and collaboration, and assignment of intellectual property rights.(Tassey, 1991, p.347)

Thirdly, within these technological parameters, the knowledge bases of particular firms are highly localised. Firms tend to have one or a few technologies which they understand well and which form the basis of their competitive position. The highly specific character of this knowledge is not simply technical: it is also social, concerning the way in which technical processes can be integrated with skills, production routines, use of equipment, explicit or tacit training, management systems and so on. At this level, the relevant technological knowledge base may be informal and uncodified, taking the form of skills specific to individuals or to groups of cooperating indiduals. The tacit and localised character of firm-level knowledge means that although individual firms may be highly competent in specific area, their competence has definite limits. This means, firstly, that they may easily run into problems in innovation which lie outside their area of competence, and secondly that their ability to carry out search processes relevant to problems can also be limited; this they must be able to access and use knowledge from outside the area of the firm when creating technologies.

These different types of knowledge base are not separate but integrated with one another, often in complex ways. Moreover they evolve over time: that is to say, technological knowledge tends not to results from generalised processes of search, but rather builds on past achievements. This gives an evolutionary character both to artefacts and knowledge, but it also implies that knowledges are both structured and cumulative over time. The capabilities of any knowledge producing institution, at a point in time, tends therefore to be a product of its past history. This introduces both into institutions and to the system as a whole a process of path dependence.

All of this suggests that knowledge bases of industrial firms have characteristics which are very different than those within the neo-classical approach. Such knowledge-bases:

- are differentiated and multi-layered, consisting of articulated forms of quite different knowledges. The creation of technological knowledge at the level of the firm is a multi-faceted process, involving the complementary development of very different types of knowledges: codified scientific results, tacit knowledges (embodied in the skills of engineers, R&D staff, workers and managers) and so on.
- are highly specific, organised around a relatively limited set of functions which firms understand well.
- are developed through costly processes of search, through processes of learning and adaptation, and are therefore cumulative, developing through time as firms build up experience with particular technologies; this in turn implies that technological knowledge is path dependant.
- are internally systemic in the sense of being part of an overall production and marketing system which has many components. in addition to multifacted technological knowledge, innovation usually involves a heterogeneous range of activities, which must be integrated and coordinated by the innovating firm. These include identifying and integrating technological and market opportunities, financing new product and process development, training, design, engineering and prototype developments, and so on.
- Are interactive and externally systemic: innovation usually involves, either explicitly or implicitly, structured interactions between institutions, involving processes of mutual learning and knowledge exchange.

3.5 Foundations of the system model

What is it about the view of technological knowledge presented above which leads to the necessity to think in terms of systems? Two important dimensions of this are mentioned here:

Firstly, the technological level itself. Advanced-economy technologies do not exist as individual artefacts: they usually take the form of integrated technological systems, in which component elements are incorporated into overall systems. Thomas Hughes, in his study of the development of rise of electricity as a dominant technology emphasized that this type of technology consists of ‘systems, built by system builders’. For such key technologies as cars, computers, and aircraft, but also for a host of less spectacular products, there is in a sense no unified knowledge base at all: product producers are in effect system managers, whose competence relies primarily on the ability to specify and integrate diverse inputs (see Mowery and Rosenberg, 1982, for examples of this in the aircraft industry, and Rosenberg 1982 for a wider overview).

Secondly, because firms are bounded or constrained in their knowledge horizons, their areas of actual or technological skill and knowledge are limited by experience and by the resources which they devote to search; this is always constrained. First, firms are often highly constrained in their ability to identify and access scientific or technological information from outside their (relatively restricted) technological environments. Second, even if they do so, there is a great gulf between having an item of technological information or knowledge, and being able to integrate it into a complex production system. But the "boundedness" of the technological horizon of firms has another dimension, of some importance for the system approach. This is that, because of constrained technological capabilities, firms attempting to innovate are always likely to run into problems which lie outside their existing capabilities and knowledge base. So although firms do not have general costless access to a generic knowledge base, or to any other form of technology-relevant knowledge, they still need to import externally-developed technological knowledge to solve innovative difficulties. This is particularly the case with emerging technologies (Fransman 1991). Of course this can and often does take the form of a market transaction: buying contract research, or consultancy services, or licensing a patent, for example. However because the need to extend or renew the knowledge base from outside is a relatively continuous activity in many innovating firms, there is always the possibility that this acquisition of external knowledge can occur through relatively routine activities which in practice lead to the evolution of systemic relationships.

3.6 The David-Foray concept of knowledge system

The David-Foray concept of knowledge system relates is narrower than the ‘national systems approach’. The latter begins from a wide understanding of technological knowledge. Lundvall’s definition is as follows:

> ... a system of innovation is constituted by elements and relationships which intereact in the production, diffusion and use of new and economically useful, knowledge ... a national system encompasses elements and relationships, either located within or rooted inside the borders of a national state (Lundvall, 1992, p.2).

The definitions offered in Nelson (1993) define innovation as “rather broadly ... the processes by which firms master and get into practice product designs and manufacturing processes that are new to them” (p.4). The system is “a set of institutions whose interactions determine the innovative performance ... of national firms” (p.4).

The David and Foray approach is in one way much narrower than this, but on another level more complex, since it seeks to produce a descriptive account of the the multi-dimensional character of scientific and technological knowledge. On the one hand, David and Foray do not look at all forms of knowledge, or related interactions, which are relevant to firm-level economic performance: they abstract from such issues as finance, marketing, design etc, which are elsewhere seen as part of the internal and external knowledge functions of firms relevant to innovation. Within the Aalborg work, financial systems, organisation and so on played an important role (e.g., Christensen 1992). The David and Foray approach focusses explicitly on “learning systems for scientific and technological knowledge”, but such knowledge is seen in a highly differentiated way, both in terms of its characteristics and functions, and its institutional features.

Firstly, relevant knowledge is classified in terms of its objects, and related actions, distinguishing between: knowledge of factual propositions; knowledge which constitutes explanations and understanding; operative knowledge for performance of tasks; and knowledge of relevant actors (see Johnson, 1992 and Lundvall, 1992). Analogous to the scheme above, technological knowledge bases are seen as either generic, infratechnological (meaning primarily methodological), applied, and product-process relevant. All of these types of knowledge can be either codified or tacit, and are produced under different modes of organization which shape different disclosure regimes.

These considerations lead to a concept of “knowledge-product space”, which is essentially a way of categorising different forms of knowledge by placing them with respect to three different dimensions (see David and Foray 1994, Figure 2, and pp.31-33):

- From completely tacit to fully codifiable
- From fully disclosed to fully restricted
- From privately owned to publicly available

The argument is that within this complex structure of differentiated knowledges, what determines performance is not so much knowledge creation as the “distribution power” of the system: the system’s “capability to ensure timely access by innovators to the relevant stocks of knowledge”. The distribution power of the system affects risks in knowledge creation and use, speed of access to knowledge, the amount of socially wasteful duplication and so on.

For the purposes of this paper, what matters are the concrete mechanisms through which such distribution occurs.David and Foray identify five processes of distribution:

- The distribution of knowledge among universities, research institutions and industry
- The distribution of knowledge within a market, and between suppliers and users
- The re-use and combination of knowledge
- The distribution of knowledge among decentralized R&D projects
- Dual technological developments (especially civil and military)

In Section 5 of this paper we explore ways of characterizing and quantifying these system elements. But before doing so, it is worth considering what we want to use such mapping for: what are the main policy challenges in a system approach of the David-Foray type?

4. Central policy issues in the 'knowledge system'

4.1 System coordination

A key policy issue arising from systems approaches is the need to identify and perhaps support nodal points in the creation and distribution system; these are likely to be changing over time: the innovation system is not a structure, but a dynamic process.. At the simplest level, the task would be to identify key points or functions within the system where public support would improve the overall distirbtiuion capability. Since knowledge system are complex in practice (even in small societies), and usually managed by quite separate institutions, there is a need for policy coordination and for adequate information systems to ensure that such coordination is possible.Actually, this problem is present even when a linear approach to policy is adopted. Although such policies are fundamentally dicovery-oriented, they tend in practice also to involve other elements: to combine basic research policies with policies aimed at developing commercial applications, at diffusion, at training, and so on. Even in the most simple linear approaches, however, systemic interactions are present: increasing resources in invention processes will slow down diffusion rates, for example, and education and training measures will always affect the ability to emphasize or de-emphasize components of the linear sequence. Most policy systems at the present time over-emphasize knowledge creation, via instruments such as R&D subsidies, intellectual property rights, and so on; even within a linear approach, there is reason to suggest that the systemic effects of this will be undesiarable (David and Foray,1994, p.16).

4.2 Externalities

The basic rational for public policy is that there are necessary activities and functions which are insufficiently fulfilled by private initiative; this usually implies an externality, and much public policy is concerned with externalities. These characteristics of knowledge which were described above have a number of implications for the externality question. On the one hand they imply that the externality effects emphasized by Arrow are *not* a significant obstacle to the production of knowledge. This means that the idea of low-cost transmission and straightforward appropriability of knowledge - as outlined in the previous section - can be misleading as a source of external benefits (Carlsson and Jacobsson, 1993, p.85). On the other hand, the knowledge system approach is one which emphasizes a wide range of interactions, some of which will take the form of non-traded flows of economically useful knowledge. There are potentially large externalities, the identification of which might be central to policy formation and operation. What forms can such externalities take? Given the general characteristics of industry-specific and firm-specific knowledge bases sketched above, we can suggest a range of forms of external knowledge. These certainly include generic "public domain" sources of scientific technological information. But they could also include: knowledge from other firms in an industry (through marketing relationships, co-operative knowledge exchange, trade literature etc); acquisition of skilled personnel; acquisition of process technologies; regulations and standards, and so on. Any identification of this must require some form of overall system mapping, with particular reference to ‘intangible’ forms of knowledge flow.

4.3 International access policies

A third important policy issue concerns the interface between national efforts and international activities. On the whole, replication is something to be avoided, although given the complexity of learning processes (especially where learning by doing is important) this is by no means an absolute. But in the context of increasingly globalised scientific and technological activities, decision problems here become very important; once again, the relevant information is system-wide.

5. Empirical identification and analysis of knowledge systems

This section deals with the empirical problem of mapping and analysing knowledge systems. It attempts to describe analytical techniques which can throw light on system profiles. The section looks first at methods for *identifying system interactions*, and secondly for *identifying system specificities and characteristics*. Each of them is intended to throw some light on the distributional modes identified by David and Foray, noted above.

It must be said that previous systems approaches have been notable more for their conceptual innovations, and the novelty of their approaches, rather than for quantification or empirical description. Lundvall (1992) is primarily a qualitative study, with the exception of two papers on trade performance; the study gives no real guide to how we might emprically define and monitor the structure and dynamics of a system. Nelson (1993) is explicitly descriptive, but with some exceptions this turned out to involve rather conventional data use on industrial structures, R&D flows, and foreign patenting. Somewhat surprisingly there was no attempt to apply a systematic set of indicators across countries, with the idea of identifying system specificities, let alone identify and map interactions. By far the most comprehensive quantitative work is Archibugi and Pianta (1992) which develops a range of indicators for identifying specialization patterns in science and technology in OECD countries.

The focus here is more on interactions than on structures. We explore currently existing data and methods, which are widely available in existing datasets, or which can be used in individual studies which are amenable to wider implementation. However understanding knowledge profiles is not something which can be achieved simply via statistical analysis; there are central qualitative dimensions which require various forms of case study (which may in fact generate quantitative data), and relevant case study methods are also indicated below.

5.1 Available data sources

It is necessary at the outset to acknowledge some basic data and source difficulties. A general problem in this field is that many the objects of analysis which we are interested in - knowledge creation and distribution, innovation activity or capability, knowledge systems etc - are intangible activities which are difficult to define. They are certainly not measurable in terms of what we normally think of as statistical variables (Grupp, 1990).

However this is not necessarily an insuperable obstacle to empirical analysis. There are three broad dimensions of this problem. Firstly, even when a concept is intrinsically unmeasurable, there may exist related indicators which provide more or less adequate proxies. Within economic theory, for example, the concept of 'welfare' is in principle unmeasurable, but we are still able to construct real income indices. Large parts of the service sector (especially public services) do not produce a measurable product, but we can nevertheless construct output variables. Such problems are very much found in knowledge-creation and use activities: we are able to construct measures which grasp particular dimensions of the process, and which can be used as overall indicators, but there remain many measurement obstacles. Secondly, it is important to recognize that some of the central data sources in this field were not designed at all for the analysis of science, technology and innovation. That is, there are certain systematic data sources which exist for other purposes, but which can be adapted for analytical purposes. This is particularly the case with patent series, which are an offspin of a legal process (the nature of which has, moreover, changed over time), and bibliometric and citation data, which exist primarily because of priority conventions in science.

A much more substantial problem is that most existing indicators tend to be relevant to 'phase' or linear models of innovation; they are not necessarily amenable to system analyses. Three primary data sources are very well known in analysis of science and technology statistics. They are Research and Development (R&D) statistics, various patent series, and bibliometric data (publication counts and citations). The common methods of using these indicators for analysis tends to rely on the type of phase model defined by Grupp:

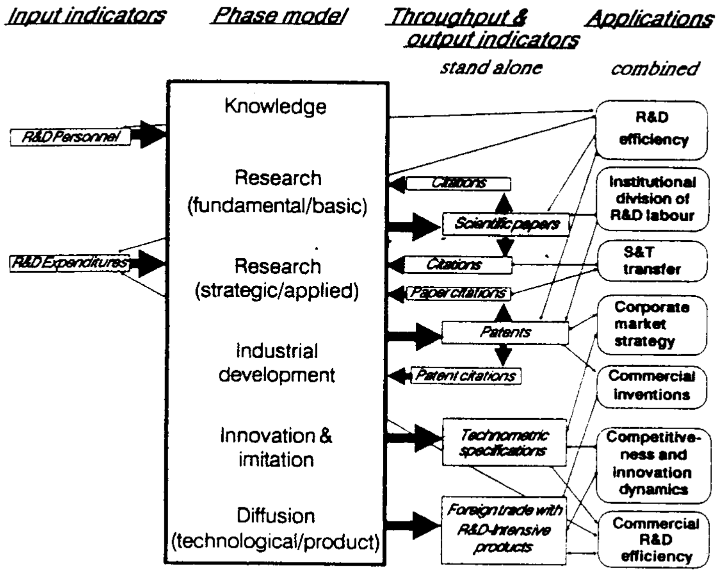

Figure 1. R&D and innovation: stages, indicators and applications
Source: Grupp, 1990, p.59

The general strengths and weakness of these sources are well-known, but they continue to have unexploited possibilities in analysis, which will be discussed below. Related data, not generally comparable between countries, is higher education data related to the training and employment of qualified scientists and engineers. These types of data tend to dominate the analysis of national systems.

However there are two major data sources, as yet not fully exploited, which are highly relevant for this area.

The first of these is the STAN (Structural Analysis) and ANBERD (Analytical Business Expenditure on R&D) datasets (for a description of both databases see

OECD 1994). A fundamental problem with many international data sets, including from the OECD, is lack of comparability. These difficulties arise from different collection periods, and from a wide range of errors and ommissions in data. This has led DSTI to develop the STAN and ANBERD databases, which integrate - in a consistent way - R&D data with data on industrial output (gross output and value-added), labour costs, employment, exports and imports, and investment. STAN and ANBERD are in turn linked with an increasing amount of (a) input-output data, and (b) bilateral trade data. The input-output database at the present time covers seven countries: Australia, Canada, France,germany, Japan, the UK and the US.

The second source is the firm-level innovation data sets which have emerged from the joint EC-OECD efforts in innovation data collection. The project is known as the *Community Innovation Survey* (CIS), and is being jointly supported and implemented by Eurostat and DG-XIII-D (SPRINT program, European Innovation Monitoring System). The primary aim of CIS is to develop and use data on the following topics:

- expenditure on activities related to the innovation of new products (R&D, training, design, market exploration, equipment acquisition and tooling-up etc).
- outputs of incrementally and radically changed products, and sales flowing from these products
- sources of information relevant to innovation
- R&D performance and technological collaboration
- perceptions of obstacles to innovation, and factors promoting innovation

CIS was implemented in 1993 in all EU Member States, and a preliminary European database on approximately 40,000 firms is now running. The data on information sources and collaboration is particularly relevant to the topic here.

Other potentially useful sources are the following:

- Data on intangible investment
- Technological balance of payments data
- Data on mobility of researchers
- Data on inter-firm technology cooperation agreements

5.2 Analysing system interactions

The basic problem in mapping knowledge systems is to identify the structure of economic and technological interactions. This section deals with the identification of types of interactions. In each case, techniques and sources are identified, with a brief discussion of how they contribute to an understanding of interactions, and of their general strengths and weaknesses. The intention here is to look at a range of quantitative measures for exploring three basic types of interactions:

- inter-industry transactions embodying flows of technological knowledge
- methods for describing patterns of use of formal scientific knowledges
- patterns of technological collaboration between firms, universities and research institutions
- measures of personnel mobility and related interactions

These types of interactions have both domestic and transnational components, and in each case the potential for transnational mapping is described.

5.2.1 Inter-industry interactions and embodied R&D flows

This section deals with some relatively well-known techniques for identification of interactions between industries; these relate to producer-user interactions in process technologies, and to the market distribution of patented knowledge.

Firms compete in large part through technological competition which improves the price-performance ratio of their product(s): they do this by improving their process technologies, and through improvements in the technological characteristics and performance of their products. By far the most important element of this is product innovation: in practice a significant part of industrial R&D is devoted to product innovation. But many of these new products are themselves input technologies, and they therefore enter as capital or intermediate inputs into the production processes of other firms and industries. Performance improvements generated in one firm or industry therefore show up as productivity or quality improvements in another, "a special kind of external economy" (Rosenberg 1982, p.71). A familiar example is computing, where large decreases in price-performance ratios (apart from producing big statistical headaches) have their major impact not on the computer industry itself but on computer-using industries (see Bresnaham 1986 for an assessment of the economic impact of this). The point here is that technological competition leads fairly directly to the intra- and inter-industry diffusion of technologies, and therefore to the intra- and inter-industry use of the knowledge which is "embodied" in these technologies.

These inter-industry flows are a very significant element in understanding the technological level or intensity of an industry, and its general innovative performance. As a recent OECD report remarks:

> Particularly for the "low technology" industries, ommission of this "indirect" technology is likely to lead to misleading policy interpretations and perhaps to an overemphasis of technology policy on the "high technology" industries where "direct" technology is more visibly and easily measured.(OECD, 1990, p.2)

Two core methods have been used for tracking these inter-industry technology flows. The first relies on the use of patents by industries other than the innovating industry. The idea here is that a patent is not simply a technique or a piece of equipment but a "carrier" of the R&D performed in the originating industry. Perhaps the best known study is by Scherer: he first established a concordance between US industrial patent classes, and the industrial R&D directed towards the technological fields covered by those patent classes, then examined the extent to which user industries used the technologies covered by these patents (Scherer 1989a; Scherer, 1989b). On this basis he constructed a kind of input-output matrix for US industry with the rows being the generating industry, and the columns the user industries; each cell contained the R&D used by a particular industry. The rows summed to the R&D performed by an industry, and the columns to the R&D used; the diagonal elements covered intramural use of process technology. Scherer showed that about

75 percent of industrial R&D flowed to users outside the originating industry, and that the inter-industry flow was positively correlated with productivity growth in the receiving industry (Scherer, 1989).

A second approach uses standard input-output techniques which map transactions between sectors and hence the flows of capital and intermediate goods. The total R&D use of an industry is then calculated on the basis of intramural R&D plus the R&D embodied in its capital and intermediate purchases. On the assumption that R&D is a private good, there are two approaches to measuring the embodied R&D. The first is as follows:

> ... the fraction of sector i's R&D that flows to sector j is determined by the proportion of i's sales of intermediate and investment flows to j in sector i's total production of such goods.(OECD, 1990, p.5)

As second method is to multiply sector j's purchases from sector i by sector i's R&D/Sales ratio. In either case the inter-industry use of R&D, plus that used in exports and final consumption, sums to the value of sector i's intramural R&D.

More interesting from the perspective here is the public good case: the assumption then is that one firm or industry's use of embodied R&D does not diminish its use by other firms or industries. At its most extreme, this implies that all users of the products of sector i have access to all the R&D performed in sector i. Scherer's solution to this problem was to assume that the largest user sector reaped all the benefits of sector i's R&D, and that smaller users reaped a share of sector i's R&D equal to their output as a proportion of the lagest using sector's output. Either way, insofar as the productivity-enhancing product innovations of sector i are not appropriated through rises in its product prices, then there is an externality, the scale of which is determined by specific or generic characteristics of the technology.

What we get from all this is not some exact absolute measure of the benefits of knowledge embodied in products. Rather, we get a set of indicators of the relative intensity of embodied-knowledge interactions between various types of industries (for a comparative study, see OECD 1993).

There are a number of possibilities which remain relatively unexploited with such techniques. One is straightforwardly to assess a debated issue in systems approaches, namely the extent and significance of internationalization. It is possible to use such datasets as STAN and ANBERD, combined with appropriate bilaterial trade datasets, to open up the imports vector in an input-output table into a matrix which indicates the industrial structure of imports, and the consequent extent of transnational embodied knowledge flows (Wyckoff 1993).

However a familiar problem in input-output approaches is their rather static character; an input-output table generates a set of input-output coefficients which are a snapshot of inter-industry relationships at a point in time, but which give no real insight into dynamic process of structural and technological change (Andersen, 1992). For this reason it is important to analyse changes in input-output structures over time, and this has recently been undertaken within the OECD. It should be noted that most OECD countries have the relevant data sources for this type of exercise, although apart from those within the STAN project there would probably be signficant problems of data management. Nonetheless this approach offers important insights both into interactions in the industrial structure, and to international components of technology flows; this or a related approach has been implemented not only for the countries in the STAN dataset but for such countries as Finalnd and Norway (Virtaharju and Åkerblom, 1993).

5.2.2 Inter-sectoral use of scientific/generic knowledges

Perhaps the most difficult area in analysing knowledge interactions is the question of links between basic science and technology creation, and specifically to the role of universities.

Although technological knowledge is not itself generic, the solution of some kind of technological problems, or the development of some kinds of technological knowledge or products, may require access to generic knowledge. Two cases should be distinguished. Firstly, various technological activities may rest on the implicit use of more or less long-standing scientific results which are in some sense the basis of a technological paradigm. This raises complex questions about what the long-run economic value of science actually is. These questions will not be addressed here. Rather we look to a second - much narrower - use of science, namely the use of general results in innovation and problem-solving. In practice such knowledge often consists of results from fundamental research conducted, for the most part, within university systems. Market transactions can occur in the use of such knowledge, but this is relatively rare: with non-market uses a technological externality exists. Two types of question are relevant here: firstly, how often do firms use publicly-accessible literature or research results in the course of innovation activity, and secondly, how significant are such results in the development of industrial innovations?

Three basic methods have been used:

- interview methods for analysing interactions in innovative problem-solving
- the use of bibliometric analysis, specifically the analysis of citations in patents
- a direct interview method for analysing use of university research.

The classic discussion of the first of these issues is Gibbons and Johnston's 1974 paper on the "mechanisms by which scientific research and education contribute to industrial innovation". Their point of departure was, in effect, rejection of the linear model of innovation - in which innovation results from prior processes of reseach discovery - in favour of an approach which saw the function of research as problem solving within ongoing innovation activities. Gibbons and Johnston examined 30 industrial innovations in the UK, all involving significant technological change. The basic method was in-depth interviewing, focussing on the types of information which were used to resolve technical problems in the development of each innovation, the number of "units" of information involved, and the source and content of the "information units". (A "unit" was defined in terms of the coherence of its content and source and involved, for example, information about the properties of materials, or relevant general laws, or appropriate test procedures). About one-third of the information used came from sources external to the firm, and of this about one-third came from what might be called generic sources: universities, scientific literature, conferences, research associations, and so on. The only traded element in the external sources of information was consultants, who supplied only 4 percent of the information units. Generic sources of information were not limited to these external sources: among what Gibbons and Johnston called "personal" sources of information, the second-largest element was education. They concluded that

> In this study, 36% of the information which contributed to the development of an innovation and which was obtained outside the company during the innovtion had its origin in basic scientific research. Of *all* the information obtained by "problem solvers" during an innovation, approximately one fifth could be similarly classified. (Gibbons and Johnston, 1974, p.230)

The Gibbons and Johnston approach has never been systematically followed up, although a number of similar case studies exist (see for example, Georghiou 1986, Part II, for a somewhat similar set of case studies). There is no obvious reason why such methods cannot be developed into a more systematic and comparable approach to university-industry links and other interactions.

A second body of research which relates generic knowledge to specific applications derives from bibliographic analysis of citations in patents. The fundamental claim of a patent is to novelty in some technical process which is also practically useful; a patent is therefore a description of the technical workability of something which is at least potentially an industrial innovation. The applicant for a patent must describe previous technique ("prior art") in the relevant field, and show the innovativeness of his or her invention; he or she therefore cites relevant literature (in many cases other patents), and the patent examiner - in testing the claims for originality and usefulness - also cites relevant work. There is now a fairly considerable body of bibliometric work analysing the extent and structure of citations to basic scientific literature in US patents, and it seems clear that in a significant number of technological fields, such citations are increasing in importance (e.g. Narin and Frame, 1989; Narin and Noma, 1985; Narin, 1988). In science-based fields such as genetics, approximately 80 percent of citations are to journals publishing basic research (Collins and Wyatt, 1988). In chemistry, a recent study concluded that "there is little distance between chemical technology patents and basic chemical science. In other words, chemical technology draws its information directly from basic chemical science" (Viannen, Moed and Van Raan 1990, p.69).

Finally, there is survey evidence on the direct use of generic information in the form of direct use of acdemic science by firms. In the course of a recent attempt to estimate a general rate of return to academic research, Edwin Mansfield interviewed R&D directors of a sample of 76 US manufacturing firms, asking them to identify product and process innovations that (a) "could not have been developed (without substantial delay) in the absence of recent academic research", or (b) "were developed with substantial aid from recent academic research". Estimates were then made of the sales flowing from such innovations; a total of $US41.1 billion of sales in 1985 derived from such products commercialised in the period 1982-1985. This was 5.1% of the total sales of major firms in information processing, electrical, chemical, instruments, drugs, metals and oil industries in the US. Process innovations relying on academic research simultaneously reduced the total costs of these industries by 2.6% (Mansfield 1991). Whatever view we take of the specific rates of return calculated by Mansfield, this kind of interview technique can be extended to other institutions, and to thus to general interactions.

5.2.3 Cooperative relationships of innovating firms

A key insight of systems analyses is the role of user-producer interactions, and the more general process of cooperation between firms. These may involve either vertical relationships between firms in a production filière, or horizontal relationships between firms within a industry, in which case they may be either competitors or producers of heterogeneous products deploying a common knowledge base. There are three basic ways in which it appears possible to explore these interactions: case studies of innovating firms and emerging industries, the analysis of data from innovation surveys, and the analysis of formal cooperation agreements.

There is now an expanding, though arguably still inadequate literature (in term of quantity not quality) of case studies on innovation processes. These case studies tend to follow either specific firms or specific innovations through a general knowledge creation process. Three broad examples will be mentioned here: the seven case studies of the Minnesota Innovation Research Programme (Van der Ven et al 1989); various case studies by Erik von Hippel and Morris Teubal, who map a wide range of forms of user-producer interactions and formal and informal exchange of know-how; and the network analyses of Håkon Håkonssen (Von Hippel 1989, Teubal 1987, Håkonssen 1989). For the understanding of systemic flows, there is a strong case for simply expanding the quantity of this type of work

An important new data source relevant to inter-institutional interaction is the output of the coordinated innovation surveys developed via the OECD, the European Commission and indivdual researchers in the early 1990s. There are two such initiatives which relate directly to the topic here: they are the Community Innovation Survey (CIS), described above, and the PACE project, which is an internationally coordinated follow-up to the Yale surveys of the 1980s.

The CIS project developed out a heterogeneous set of more or less independent surveys carried out by private researchers in the 1980s (see OECD 1990; Smith, 1992 for descriptions); in 1992 the experience of the surveys was sythesised into an OECD manual, which aimed at improving the conceptual and statistical coherence of future surveys (OECD, 1992). The OECD approach was subsequently developed by the Eurostat and DG-XIII (European Innovation Monitoring System) within the European Commission, and implemented on a EU-wide basis; this survey was known as the Community Innovation Survey (CIS) (the data will henceforth be refererred to as ‘CIS data’). Eurostat is now building a comprehensive firm-level database with the CIS data, which will when completed contain data on approximately 40,000 European firms (see European Commission, 1994 for an overall description). A closely similar approach has been adopted and has been or is being implemented in Canada, the USA, Norway, Finland and Australia.

The CIS survey primarily collects data on activities related to new product innovation in manufacturing, and on outputs of new or improved products within the sales profiles of firms. But it also contains several questions on technological cooperation and information flows, and it therefore makes it possible to link up the general innovation performance of firms with their patterns of technological collaboration and information use. There are two sets of relevant data from the survey, on information sources, and collaboration. The PACE project asks a closely similar set of questions, but to a very different population of firms: the CIS survey is aimed at the manufacturing sector as a whole, via a stratfied sample with generally low cut-off points; it is not specifically aimed at R&D-performing firms. The PACE survey is aimed at large R&D-performing firms, invariably with more than 500 employees. The surveys are therefore complementary.

First, the questionnaire asks firms to rank, on a 5-point ordinal scale, the importance of the following “types of information required in the development and introduction of technological change”:

INTERNAL SOURCES
-within the enterprise
-within the group of enterprises
EXTERNAL/MARKET SOURCES
-suppliers
-clients and customers
-competitors
-joint ventures
-consultancy firms
EDUCATIONAL/RESEARCH ESTABLISHMENTS
universities/higher education
government laboratories
technical institutes
GENERALLY AVAILABLE INFORMATION
-patents
-professional conferences, fairs/exhibitions/meetings
-professional journals
OTHER EXTERNAL SOURCES

Secondly, the questionnaires asks about acquisition and transfer of technology. This is simply a binary (yes/no) question, in which firms are asked whether they use a particular channel of transfer or acquisition, and where the source is located geographically. This covers a number of key forms of knowledge flow, including licences, contracted R&D, consultancy services, mergers and acquisitions, communications wioth other enterprises, or hiring policies. One of the interesting possibilities with the overall dataset is actually to explore the effects of cooperation: for example to test links between cooperation channels and other innovation activities and outputs of firms. This dataset has only recently been established, so it is too early to suggest results, but a preliminary result from the Norwegian survey suggests that firms active in cooperation arrangements with other institutions have significantly higher levels of new product sales than those not engaged in cooperation; this result seems to be rather robust, applying across all industries and size-classes of firms.

The PACE questionnaire is far more wide-ranging, as well as more specific, than the CIS survey: it asks firms for 5-point ordinal rankings of the importance of three broad types of knowledge flow or support: technological knowledge, research outputs and methods of access to these outputs, and public sector policies. The main dimensions of the information generated by the project are as follows:

SOURCES OF INFORMATION
- parent firms or subsidiaries
- joint ventures
- suppliers
- customers
- universities
- public conferences

OUTPUTS OF RESEARCH
- use of basic research results
- specialized knowledge
- instrumentation
- prototypes
- trained researchers or scientists

METHODS OF ACCESS
- publications
- conferences
- hiring
- personal contacts
- funding R&D
- joint R&D

PUBLIC POLICIES
- procurement policies
- subsidies
- R&D support
- inforamtion programmes
- cooperation programmes
- agencies for accessing international information

It is clear that these types of new data offer major opportunities in system mapping. There are, of course, many potential pitfalls with them, and the general quality of this data will need serious evaluation. But the prospects for policy-relevant system mapping look very promising.

Finally, there exist methods for mapping specific cooperation agreements by firms: here an extremely wide literature already exists, although there has been no real discussion of whether there are might be benefits to come from standardised approaches, and if so, how they might be developed. In a comprehensive survey, Chesnais (1988) described six main categories of such studies:

- Studies on joint ventures between firms
- Industry case studies, reporting incidentally on cooperation
- Studies of inter-firm cooperation agreements in general
- Technological collaboration in specific industries
- Business management studies (on cooperation and corporate strategies)
- Institutional studies of cooperative R&D in different national environments

The literature on these topics is particularly large, but has not - apart from Chesnais's work - been explored from a policy perspective; there appears to be considerable scope for using such literature in national policy contexts. It should be noted that it is possible to build quite substantial and consistent data sources on this issue: the MERIT-CATI databank in particular collected data on over 7,000 cooperation agreements, and has generated excpetionally interesting analyses of knowledge interactions (for an example, see Hagedoorn and Schakenraad, 1990).

5.2.4 Personnel mobility

An important element in system interactions is occupational mobility. Data on stocks of researchers and qualified scientists and engineers is quite widely available, and use din comparative studies. Flows are more problematic. However, a number of studies in various countries have shown that mapping such mobility with survey techniques is practicable, and a number of OECD countries have mobility data which throws some light on interactions between major research-performing sectors. At the simplest level there is simply data on mobility rates from universities and research institutes, combined with patterns of recruitment and destinations when leaving. This data is available, in more or less partial form, for most European research institute systems (see Ekeland and Wiig, 1994). Their study of the Norwegian system showed that the substantial sector of technological research institutes recruited researchers primarily from the university sector after post-graduate study, and sent personnel to the business sector; annual turnover rates average about 7%, and most of those moving do so within six years. The general picture which emerges is one of a stable interaction pattern, in which publicly supported research institutes play a key role in supplying skilled personnel to business. For some countries such data is supplemented with data on 'partial' mobility, meaning periods on sabbatical, loan, contract research and so on. In general, this is an underdeveloped research area, but one where data exists and is relevant to knowledge system interactions.

5.3 System specificities

Ths far, this paper has explored methods for identifying interactions within systems. But such interactions should be placed within a view of system structures and specificities. There are a number of relatively straightforward indicators which are relevant for policy analysis, but which could be more widely used. These include, for example, the Revealed Comparative Advantage (RCA) and Revealed Technological Advantage (RTA) indicators, various patent indicators indicating degrees of self-sufficency or external dependency, and so on. There exists one systematic attempt to use all of the available science and technology indicators to identify such specificities, namely Archibugi and Pianta (1992); further analysis of system approaches could involve a development of their work.

There is one particular indicator, widely used, where system specifities ought to be tken into account, and ought to modify the policy use of the indicator. This is the use of R&D intensities for international comparisons. In comparing the R&D performance of companies, industries or countries, we clearly cannot use absolute amounts of R&D expenditure or employment, if only because there are large size differences between countries. To overcome this, there is one overwhelmingly popular indicator, namely "R&D Intensity". For an economic sector, such as manufacturing or services, or an individual industry, this is usually defined as the ratio of R&D expenditure to Value Added or gross output. For an entire economy the equivalent measure is R&D/GDP. These ratios are widely used and are the usual basis for distinguishing between high-technology, medium-technology and low-technology industries. The R&D Intensity indicator can be extremely useful, but it can also be misleading. This is particularly the case if we simply compare the overall R&D Intensity numbers for manufacturing sectors as a whole. It is not uncommon for rather sweeping policy conclusions to be based on such comparisons. This kind of policy conclusion is oversimplified and unjustified. The reason for this is that the overall R&D Intensity for any country is strongly affected by what kind of industries the country possesses. The overall R&D intensity is an effect of two separate things - on the one hand, how much R&D is performed in the various industries, and on the other, the mix of low and high-R&D industries which the country possesses. If Country A has an industrial structure which is based on low-R&D industries, then it will have a lower overall R&D Intensity than Country B which possesses more (or larger) high-R&D Intensity industries. This is a matter of arithmetic rather than research performance, and under certain circumstances Country A can have a lower overall R&D Intensity than Country B even if it has *higher* R&D intensities in every single industry. The OECD has proposed a structure- adjusted indicator, called STIBERD, which attempts to take account of these structural impacts (see OECD 1994, pp.51-55); use of such indicators is central to reasonable structure analyses.

5.4 'Institutional mapping'

What has been presented above is a kind of portfolio of mapping techniques which, taken together, can give us some first approximations of system interactions and characteristics. However it is important to note a significant limitation in such statistical exercises, which is that they tend to erase one of the most important insights of the knowledge system approach, namely institutional differences. It therefore seems important to link any quantitative approach in this field with qualitative approaches which map institutional differences: for an example of this, in the 'national systems' context, see Mjøset (1992).

Knowledge systems are characterised by institutional complexity. On the private level, technology infrastructure institutions include industry associations and conferences, training centres, trade publications, collectively established technical standards (such as architecture and operating systems in computing), branch research institutes and so on. Public sector institutions include research councils, standards-setting organisations, patent offices, universities, research institute systems, libraries and databases. Public sector instruments include R&D programmes, legal or administrative regulations, subsidies to capital stocks (especially structures and scientific equipment), and public procurement. We could define the public science and technology infrastructure as consisting of a combination of these institutions and the flow of resources through them.

However the nature of these institutions may vary considerably between countries. Consider, for example, 'universities'. Of course all OECD countries have university systems. But there is no definitive form for universities: they can have many different organisational structures, many different links with society, many different approaches to how knowledge is generated, and how teachin shold be undertaken, and so on. Even with national boundaries there can be surprising diversity of forms: the USA is simply the most striking example of this. The potential diversity is even greater in an international context.

These rather elementary points raise wider questions about the nature of institutions: how do they evolve, what is the scope for policy intervention in their evolution? These issues are at least as central to comparative analyses as the quantitative procedures described above.

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STEP-gruppen ble etablert i 1991 for å forsyne beslutningstakere med forskning knyttet til alle sider ved innovasjon og teknologisk endring, med særlig vekt på forholdet mellom innovasjon, økonomisk vekst og de samfunnsmessige omgivelser. Basis for gruppens arbeid er erkjennelsen av at utviklingen innen vitenskap og teknologi er fundamental for økonomisk vekst. Det gjenstår likevel mange uløste problemer omkring hvordan prosessen med vitenskapelig og teknologisk endring forløper, og hvordan denne prosessen får samfunnsmessige og økonomiske konsekvenser. Forståelse av denne prosessen er av stor betydning for utformingen og iverksettelsen av forsknings-, teknologi- og innovasjonspolitikken. Forskningen i STEP-gruppen er derfor sentrert omkring historiske, økonomiske, sosiologiske og organisatoriske spørsmål som er relevante for de brede feltene innovasjonspolitikk og økonomisk vekst.

The STEP-group was established in 1991 to support policy-makers with research on all aspects of innovation and technological change, with particular emphasis on the relationships between innovation, economic growth and the social context. The basis of the group's work is the recognition that science, technology and innovation are fundamental to economic growth; yet there remain many unresolved problems about how the processes of scientific and technological change actually occur, and about how they have social and economic impacts. Resolving such problems is central to the formation and implementation of science, technology and innovation policy. The research of the STEP group centres on historical, economic, social and organisational issues relevant for broad fields of innovation policy and economic growth.