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Universities and industrial transformation

An interpretative and selective literature study with special emphasis on Sweden

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An interpretative and selective literature study with special emphasis on Sweden*

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1. Introduction

In a 'knowledge-based' society, much attention needs to be given to the role of universities in contributing to technical change and economic growth. Indeed, science, technology and educational policies may well be argued to be the heart of any government efforts to promote economic transformation. However, although Marx argued that science had become a powerful productive force as early as in the 19th century, our knowledge of the behaviour of universities, of the interactions between these and industry and how to measure the value of academic research is still quite limited. Policies are therefore, as in other fields, based on beliefs about 'how things work' and on the relative strengths of various pressure groups. In the following, we will attempt to come to grips with what we know, what we do not know and what questions may be worth pursuing; in particular with respect to emerging knowledge fields. The purpose of this paper is, thus, to make a selective and interpretative review of the very large literature on university-industry relations with the aim of identifying questions for further research.

In section two, we will provide the 'bare bones' of an analytical framework for approaching university-industry relations in that we make explicit our view of the innovation process, the role of the universities in that process, and how it may differ between knowledge fields and over geographical regions. In the following three sections, we address three themes with a strong bearing on science and educational policy. Discussing these themes, we will refer to the Swedish situation as much as possible. In section three, we discuss how to measure *the size and performance of academic research*. Here, we take our point of departure in a current Swedish policy debate. The next theme, dealt with in section four, is *assessing the value of academic R&D* where we discuss a number of sources of uncertainty and what these may mean for policy. The final theme is *improving the value of the academic sector* where we deal with the issue of 'responsiveness'; i.e. how rapidly universities react, in terms of both research and education, to the emergence of new knowledge fields and how it may vary depending on governance structures and other factors. The final section contains a specification of a set of questions that need further research.

2. Universities and the innovation process – a broad framework

2.1 Introduction

Any enquiry into the relationship between universities and the transformation of industry needs to be clear about how the innovation process, and the role of the universities therein, is conceptualised. This section sets out to do so. We begin by outlining the relationship between the 'chain-link' model of the innovation process and that of innovation systems, arguing that these are complementary. We then propose that it is useful to analyse the workings of innovation systems by focusing on a set of functions that need to be performed if a system is to perform well. One provider of these functions is the university. There are various mechanisms through which the benefits of academic R&D can accrue to industry (i.e. how universities can contribute to functionality) and these benefits lie less in codified 'results' as in access to capabilities and tacit knowledge. The benefits of academic R&D are often, therefore, localised. The extent of these benefits, and the manner in which they are reaped, depend on the nature of the (regionally constrained) innovation system in which universities form a part as well as the character of the specific innovation process in various knowledge fields.

2.2. The chain link model, innovation systems and functional analysis

The innovation process is still often seen as a flow 'down a one-way street' (Kline and Rosenberg, 1986, p. 285) where research leads to development, development to production, and production to marketing. As has been noted by many, there are serious shortcomings in this conceptualisation of the innovation process.[1] Perhaps the most important are the lack of feedback paths, an associated unidirectional view of the causal relationships, and a simplistic view of the role of science (Kline and Rosenberg, 1986).

Feedback is essential, and takes place between users and suppliers, between various phases in the design process, between production and design and between all these and science. The relationship between science and design is complex in that some designs are made without a corresponding science base, whereas other design developments spur scientific enquiries (i.e. the interaction goes both ways)[2] and yet in other cases, scientific advances lead to new designs. Finally, where science is involved in design development, the bulk of the knowledge used refers to the accumulated stock and the results from current research form but a small part of the whole.

The ‘chain-link model’ developed by Kline and Rosenberg (1986) considers the above features of the relationship between science, technology and market and provides us with a useful conceptual starting point for studying the relationship between university and industry. Two features of the model stand out. First, science is not seen as the initiator of change but is visualised as being parallel to the development and marketing process – to be used when needed. It is only when accumulated science fails to solve problems arising at any point in the innovation and diffusion process that research is undertaken. Second, there are many pathways, not only one. These are:

- Potential market⇒analytic design⇒detailed design⇒ redesign⇒produce⇒distribute and market
- Feed back loop from ‘distribute and market’ to ‘potential market’ and between all the other phases
- Reference to accumulated science, and if that fails, to research, from any of the stages
- New products opening up for new science (e.g. the microscope)
- New science leading to new designs (e.g. genetic engineering)

The model suggests that the role of universities in technical change should not be seen as limited to pursuing research ‘at the frontier’ but, instead, a central function is to make accumulated knowledge available as and when there is a need for it; the university could be seen as a reservoir of knowledge. This reservoir is, of course, transferred primarily through teaching, at both the undergraduate and the graduate levels, but transfer also takes place in various fora where industry meets academia. In these fora, moreover, information and knowledge flow in both directions for at least two reasons. First, basic and applied research is undertaken outside of academia (indeed, in some areas, industry dwarfs academia, see Granberg and Stankiewicz,

1981) and, second, problems encountered 'downstream' play an important role in guiding work 'upstream'.

Only implicitly are there, however, actors such as universities or capital goods producers in the model. Nor are there networks through which interactions are conducted, or institutions regulating behaviour, or mechanisms through which university interacts with industry. In order to help us improve our understanding of what shapes the formation of the accumulated knowledge base, the links between different phases in a particular country or region, and ultimately the role of universities in technical change, we need to add an innovation system approach to that of the 'chain-linked model'.

While there are many related innovation system approaches, let us use a technology specific one as it focuses on competences and knowledge, which seems particularly appropriate when the object of enquiry is the universities and their links to industry. A technological system is defined as (Carlsson and Stankiewicz (1991, p. 21):

> "…network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology. Technological systems are defined in terms of knowledge and competence flows rather than flows of ordinary goods and services."

A technological system is made up of three main elements:[3]

Actors and their competences, technical as well as others. These may be firms or other organisations. A particularly important set of actors is 'prime movers' or system builders (Hughes, 1983). These are firms, or other actors, which are technically, financially and/or politically so powerful that they can strongly influence the development and diffusion process. For instance, a prime mover may be a 'lead user' providing suppliers with feedback on existing products and ideas for new products. Other notable actors are those that form bridges between academia and industry and those shaping the science and educational policy of a country or region.

Networks that constitute important channels for the transfer of both tacit (Metcalfe, 1992) and explicit knowledge. Networks may be conducive to the identification of problems and of the development of new technical solutions. They may also be conducive to a more general diffusion of information. Being strongly integrated into a network increases the resource base of the individual firm, and other actors, in terms of gaining access to information and knowledge. The network also influences perceptions of what is desirable and possible, in that it shapes our images of the future, which in turn guide specific decisions, be they in firms or in other organisations.

Institutions, which stipulate the norms and rules regulating interactions between various actors (Edquist and Johnson, 1997) and define the value base of various segments in society. The roles of institutions vary: some influence the connectivity in the system whereas others influence the incentive structure. Yet others may shape the governance structure of the higher educational sector. As is emphasised in institutional economics (e.g. Edquist and Johnson, 1997), and in the literature on innovation systems (e.g. Carlsson and Stankiewicz, 1991; Porter, 1998), institutions are important not only for the specific path a technology takes but also for the transformation of industry.

Technological systems are, of course, not static but inherently dynamic and unstable. The dynamics can be viewed as a function of a tension between the logic of technology and the nature of actors, networks and institutions. Any change in one component in the system may trigger a set of actions and reactions that relieve the tension and propel the system forward. The boundaries, in terms of both actors and knowledge, may consequently alter, sometimes quite rapidly (Carlsson et al., 2002).

The approach, thus, assumes that the emergence of new technologies, and the subsequent transformation of industry, does not take place in a vacuum but rather through a dynamic interplay between firms and other organizations, such as universities, industrial associations and government bodies; and that the nature of the institutional framework heavily influences the process. In this, the approach underlines the many and complex links depicted in the 'chain-link' model, but adds an understanding of what shapes the nature of the links and the accumulated knowledge base in a particular country or region.

2.3 Functions in an innovation system and the mechanisms which influence functionality

A useful way of analysing the emergence and diffusion of a new technology is to focus on how a set of *functions* is performed (Johnson and Jacobsson, 2002, Rickne, 2000). These functions constitute an intermediate level between the components of a technological system and the performance of the system. An extensive review of the innovation system literature (Johnson and Jacobsson, 2001, Bergek, 2002), suggests that there are five basic functions that need to be performed in a technological system:[4]

- Create and diffuse *'new' knowledge*
- Influence *the direction of search processes* among users and suppliers of technology. This function includes guidance with respect to the growth potential of a new technology, which may be closely linked to the legitimacy of it, and guidance in relation to choice of specific technology.
- *Supply of resources* of both general nature such as capital, competence and input materials and those which are intimately linked to the specific innovation and the actor's receiver competence.
- *Create positive external economies*, an example of which is the formation of buyer-seller linkages or networks that provide 'spill-over' effects by the synergetic creation of knowledge, reduction of uncertainty, guiding the search process, reducing the cost of information, accessing tacit knowledge and sharing of costs
- *Form markets* since innovations rarely find ready-made markets, but these need to be stimulated or even created. This process may be affected by firms' marketing efforts but also by government actions to clear legislative obstacles and by the measures of various organisations to legitimise the technology.

The functions are not, of course, independent of one another and a change in one function may lead to changes in other functions (Rickne, 2000; Johnson and Jacobsson, 2001). For instance, the creation of an initial market may influence the direction of the search process and lead to entry by new firms that bring new resources to the industry. The linkages between functions may also be circular, which may set in motion a virtuous circle, or a process of cumulative causation (Myrdal, 1957). For instance, the resources brought into the industry by a new entrant may be used to develop the market further.[5] Powerful virtuous circles lie at the heart of an expanding technological system but it may be extremely difficult to set them in motion. For instance, in the case of the technological system related to the generation, diffusion and use of solar cells in Germany, two decades passed between the initiation of large R&D programmes and the emergence of a process of cumulative causation (Jacobsson, et al. 2002).

There are two main reasons for analysing dynamics in functional terms rather than purely in terms of the dynamics of each of the components of the technological system. First, there is no reason to expect a particular configuration of a technological system, or structure, to be related to the performance of the system in a clear and unambiguous way. By arranging our empirical material in terms of functions, we can trace the way in which a particular entry/exit pattern, actor combination or a specific institutional set-up[6] shapes the generation, diffusion and utilisation of new technology. Second, we can define the border of the system, an inherently very difficult task (Carlsson et al. 2002), by analysing what promotes or hinders the development of these functions (Johnson and Jacobsson, 2001).[7]

In summary, we have a framework that provides us with a tool for analysing the dynamics of a technological system through capturing not only *how* the functional pattern of an innovation system evolves, but also the extent to which *virtuous circles* exist and what *factors and actors shape* the process.

One of these actors is the universities, which can contribute to all of the functions listed above. ‘Create and diffuse knowledge’ refers not only to the pursuit of groundbreaking research but also to the diffusion of knowledge from the accumulated stock in the world. A university can influence ‘the direction of search processes’ in industry through enlarging the technological opportunity set, by examining PhDs in new fields, by demonstrating the usefulness of a specific design approach etc. The role of the universities in the ’Supply of resources’ may refer to the supply of an adequate volume of both undergraduates and graduates in a particular knowledge field, e.g. electronics, or, a more detailed field, in microwave technology. It may also refer to the supply of capital, in particular seed capital and other essential resources for spin-off firms. Universities can help to prepare the ground for the ‘Creation of positive external economies’ by providing meeting places, and through participating in various types of bridging organisations and in joint R&D with industry. Finally, the universities can contribute to the ‘formation of markets’ by being an innovative customer, for instance in instrumentation.

Hence, at the general level, *we can conceptualise the role of the universities in the innovation and diffusion process as a provider a whole range of functions*.[8]

As hinted at above, there are various *mechanisms* by which universities may perform these functions and the influence can be both direct and indirect. Some of these mechanisms are listed below (Meyer-Krahmer and Schmoch, 1998; Pavitt, 1998; Salter and Martin, 2001). [9] The first three refer to the traditional mechanisms of publishing and of teaching. The fourth and fifth emphasise the role of various types of networks, meeting places and markets for the sharing of information and knowledge whereas the last two point to the development of products and firms by academics.

- Scientific publications which expand the technological opportunity set of firms
- Training of engineers and natural scientists
- Training of PhDs with its essential provision of background knowledge, skills and personal networks
- Participating in common informal networks, joint R&D projects, research funding and contract research with an associated sharing of explicit and tacit knowledge (gained through research and being members of national and international professional networks)
- Linking national firms to international networks and providing access to explicit and tacit knowledge from a wider range of sources
- Development of instruments and engineering design tools
- Spinning off technology-based firms

It would seem reasonable to divide these into primary, secondary and tertiary mechanisms. The primary one is research, the secondary is teaching at PhD and undergraduate levels, while the tertiary mechanisms refer to the remaining ones. Taken jointly, it is through all these mechanisms that academic research increases the rate of return of private, more applied R&D.[10]Without high quality capabilities in research, academics will not be able to provide such a meaningful contribution to industry and society, even if the remaining mechanisms are employed.

Implicit in the list, is that there are many types of benefits accruing from academic research and these go far beyond providing new information of a public good nature but include: diffusion of tacit knowledge, access to a pool of highly skilled labour, provision of background knowledge,[11] assistance with experimentation, formation of networks etc. In an authoritative review, Salter and Martin (2001, p. 528) underline that "…these benefits are often *subtle, heterogeneous, difficult to track or measure and mostly indirect* (our italics)."

In a rare study which traces the mechanisms used, and the benefits of academic R&D in three knowledge fields, Faulkner and Senker (1994) conclude that: "In particular, our approach privileges the role of informal linkages; flows of tacit knowledge; and the wider contribution of public sector research to industrial innovation through the literature and training". Pavitt (1991, 2001) and Salter and Martin (2001) point to skilled graduates as the main mechanism through which the benefits of research flow into industry.[12]

Yet, the public debate has recently focussed more on the last mechanism (formation of firms) and on the associated issues of patenting, incubators and seed funding related to the 'entrepreneurial university' (see e.g. Etzkowitz et al, 2000). Whereas it is clear that substantial (and well motivated) changes have been made to improve the functioning of this mechanism, it is nevertheless only one of many, but perhaps one of the easier to measure. *An appropriate science policy needs to scrutinize the functioning of all the mechanisms, including those, which are less easy to track, and which clearly are of great importance to industry.*

2.4 Spatial and knowledge specific interactions between university and industry

The emphasis on training, tacit knowledge and indirect benefits, rather than codified information (or even products) as the main output of academic research suggests that there may be a strong spatial dimension[13] in the distribution of those benefits. As Pavitt (1998, p. 797) puts it:

> "…the main practical benefits of academic research are not easily transmissible information, ideas and discoveries available on equal

> terms to anyone in the world. Instead, they are various elements of problem-solving capacity, involving the transmission of often tacit (i.e., non-codifiable) knowledge through personal mobility and face-to-face contacts. The benefits therefore tend to be geographically and linguistically localised."

Similar conclusions are drawn in other studies on university-industry interaction (e.g. Hicks et al. 2001; Blind and Grupp, 1999; Mansfield and Lee, 1996; Salter and Martin, 2001) as well as in the vast literature on 'spill-overs (e.g. Anselin et al. 1997).

This literature could be seen as a sub-group of the larger literature on regional and national innovation systems where a key element is a set of spatially constrained externalities mediated through market or non-market mechanisms and governed by a specific institutional set-up (e.g. Carlsson and Jacobsson, 1991; Lundvall, 1992; Saxenian, 1994; Edquist, 1997, Carlsson; 1997; Rickne 2000; Holmen, 2001).

The extent to which, and how, universities contribute to functionality would, therefore, be expected to depend on the context in which they are placed (in addition to factors internal to the university); i.e. on the nature of the spatially constrained innovation system. Clearly, there are features in the specific technological systems which should be expected to be influential (Faulkner and Senker, 1994; Meyer-Krahmer and Schmoch, 1998). Some obvious factors would be the R&D strength of the relevant industry (greater strength leads to more interaction); the size structure of firms (larger firms may lead to more formal interaction); science and educational policies (e.g. the size of funding and the orientation of funding) which affect the strength of the academic research base and the quality and volume of 'output' of graduates in particular fields; the existence of a developed venture capital market; the functioning of various bridging institutions and the prevalent values as regards industry-academia collaboration. Hence, any analysis of the benefits of academia, and the mechanisms through which these benefits flow, need to include a whole range of features in the surrounding innovation system.

In addition to varying across space, we would also expect the extent to which, and how, universities contribute to technical change is likely to differ between knowledge fields (Faulkner and Senker, 1994; Salter and Martin, 2001).

The ways in which innovations are generated vary between industries (Kline and Rosenberg, 1986). They may differ in several dimensions and we probably do not have enough knowledge of the diversity involved. A dimension, which has received much attention lately, is the science dependency of innovations (Narin et al., 1997; Meyer-Krahmer and Schmoch, 1998; Meyer, 2000; Hicks et al., 2001; Tijssen et al., 2000 and Tijssen, 2002). This is usually measured by the frequency of references to scientific publications in patent applications and shows very distinct differences between various knowledge fields. Biotechnology, pharmaceuticals and semiconductors rank highest whereas civil engineering and many mechanical engineering fields rank among the lowest (Meyer-Krahmer and Schmoch, 1998).

This is not to be construed as science-based technologies following a linear model of development (where there is a direct link between scientific development and technical change), but only as science figuring prominently as an input into the process; the relationship is, again, more likely to be indirect than direct. As Meyer (2000, p. 425) concludes from an in-depth study of a small number of patents in nano-technology:

"The evidence…supports the view that there is a general connection between science and technology, but points out that citation linkages hardly represent a direct link between cited paper and citing patent ... Scientific findings are important background knowledge playing an important indirect rather than direct role".

A related dimension is whether the innovation process is discovery or design driven (or rather, where on a continuum a knowledge field is placed; Granberg and Stankiewicz, 2001). A research-based discovery driven process can be seen in virtually all biotechnologies and in many material technologies as well as in some energy technologies (Granberg and Stankiewicz, 2001). The search process is opportunity driven and takes place within poorly articulated 'design spaces', it is highly empirical and prone to serendipitous discoveries. A design driven process is more often demand driven and takes place within a well articulated design space where problems are solved though what Kline and Rosenberg (1986) call 'analytic design'. Mechanical and electrical engineering as well as computer science operate largely under this design regime.

Hicks et al.'s (2001) careful analysis of patent data gives support for the relevance of this dimension. It shows that patenting in information technology has a very different pattern to that of health sciences, in that the former does not refer much to science, it refers to technology which is on average newer than the science it cites and the technical documentation cited is often non-research technical work. Meyer-Krahmer and Schmoch (1998) similarly argue that the cognitive structure in knowledge generation varies between fields and that mechanical engineering, in contrast to chemistry and electronics, has tangible artefacts, which are open to direct, experience based, manipulation and where much work is geared towards the optimisation of products and processes. This should, again, not necessarily be construed as suggesting that the relationship between industry and university is necessarily weak in mechanical engineering, but that the mechanisms used may be different.

Available empirical evidence also suggests that there is a considerable difference in the nature of the relationship between university and industry in scientific fields, technologies and industries (Kline and Rosenberg, 1986; Faulkner and Senker, 1994; Rosenberg and Nelson, 1994; Meyer-Krahmer and Schmoch, 1998; Rappert et al. 1999; McMillan et al., 2000). For instance, Faulkner and Senker (1994) argue that differences in the extent of university-industry in three knowledge fields (biotechnology, ceramics and parallel computing) can be, at least partly, explained by the nature of the innovation process (engineering design versus science) where the latter two fields are less reliant on links to universities and more dependent on other firms in the supply chain (e.g. the importance of feedback from the users of ceramics is very important). Formal linkages in terms of R&D contracts and literature scanning are relatively more important in biotechnology, whereas in parallel computing, informal linkages and personal contacts matter more. In the public sector, research acts as both the customer and a supplier of specific knowledge.

McMillan et al. (2000) and Rickne (2000) underline the role of close links with academic research in biotechnology; citations of (public sector) basic research figure prominently in patents, many firms are spin-offs from universities and a range of formal and informal links tie academia closely to industry.

Meyer-Krahmer and Schmoch (1998) analysed university-industry interaction in five different fields (production technology, microelectronics, software, biotechnology and chemistry) and found that overall, collaborative research and informal contacts were most important. In line with the argument above, they conclude that: "Obviously, industrial researchers have become members of informal networks wherein academic as well as industrial researchers discuss their research projects and findings" (Meyer-Krahmer and Schooch, 1998, p. 841). There are, however, differences between the respective fields in the importance of various mechanisms; in mechanical engineering, the main mechanism used is contract research to solve specific technical problems, whereas in chemistry, the provision of personnel and education is the most important mechanism.

Clearly, therefore, there is a considerable difference in the pattern of interaction in different knowledge fields. The precise reasons for these patterns are, however, not fully known, but are presumably to be found in a combination of knowledge and spatial specific features.

To conclude, we conceptualise the role of the universities as a contributor to a set of functions, the fulfilment of which shapes the evolution of technological system(s) and their performance. The mechanisms employed to benefit industry are many as are the types of benefits. The benefits are often subtle, difficult to trace and measure, and mostly indirect. Both the benefits and the mechanisms used would be expected to vary depending on the specific knowledge fields and on the nature of the technological system(s) in which the universities form but a part.

In the next sections, we will explore three themes of specific relevance to the science policy debate in Sweden. The first refers to problems associated with measuring the strength of the academic sector. This is, as we shall see in the case of Sweden, an important issue as misspecification of the strength (or weakness) would be expected to influence our perception of the main research questions and policy issues. The traditional, and the core functions, of the universities, is to develop knowledge and to train engineers and scientists. Science policy shapes the evolution of the knowledge base and the formation of capabilities and, therefore, shapes what can be developed (in terms of technology, products and firms) or transferred via formal or informal links. The second theme is the inherent difficulties involved in assessing the value of academic research, and how various ways of assessing it may shape the quality and variety of the knowledge and capabilities generated in the academic sector. The third theme is highly related to the second one, as it explores the speed and the strength by which universities develop knowledge and capabilities in new fields, i.e. their 'responsiveness'.

3. Measuring the size and performance of academic R&D - to what extent is Swedish academia a 'powerhouse'

Sweden is seen as a top-performing nation in terms of academic research (e.g. Salter et al. 2000; Sörlin and Törnvist, 2000). Indeed, Sweden has recently been labelled an academic 'powerhouse' (Goldfarb and Henrekson 2002).

The Swedish *share of academic R&D in GDP* is the highest in the world (Pavitt, 2001, Salter et al., 2001, table 5) and about double that of the average of the OECD countries (Henrekson and Rosenberg, 2000). Likewise, Sweden is in the top few (no. 2 and far above countries such as Germany) in terms of the *number of scientific articles published* (in science and engineering) set in relation to GDP (Henrekson and Rosenberg, 2000; Vinnova, 2001) as well as in terms of how often these articles are *cited*, an indicator of the quality of R&D (Lattimore and Revesz, 1996;[14] Vinnova, 2001; Pavitt, 2001).

Recently, these observations were used as the starting point for a discussion which contrasts this apparent strength of Swedish academia with poor performance in terms of technology based entrepreneurship, a weak high technology sector, and poor economic growth (Sörlin and Törnqvist, 2000; Henrekson and Rosenberg, 2000 and Goldfarb and Henrekson, 2002). Much of the analysis focuses on the lack of incentives to exploit university generated knowledge. In particular, Henrekson and Rosenberg (2000) provide a thorough discussion of a set of problems with the incentive structure in Sweden, especially in relation to university-based entrepreneurship. They also raise the issue of how well the fairly recently created mechanisms for the 'transfer' of technology to industry may work, as compared to more spontaneous interactions generated in innovation systems with a more decentralised and competitive university system combined with greater incentives to exploit technology through start-ups.[15] As technology development and diffusion are endogenous to an innovation system, and as incentives form an important part in the working of an innovation system, it is undoubtedly so that a set of important issues have been raised.

Yet, we will argue that the perception of Sweden as an industrially under-utilised 'academic powerhouse' is somewhat exaggerated. We will not only argue that there are methodological problems involved in using both R&D expenditure and publication data but also that more recent data on the performance of Swedish industry may lead to a somewhat different picture of the current state of industry than what is reflected in the literature referred to above.[16]

As Sörlin and Törnqvist (2000) note, the share *of publicly financed R&D* that is undertaken in the academic sector is unusually high in Sweden. In countries such as Germany and the US, much R&D is performed in various types of institutes. We would expect that the R&D pursued in such institutes does not only result in immediately useful technology. Work of a more basic character as well as academic publishing is clearly not solely done at Universities. For instance, in Germany, both basic and applied work is done, and papers are published in the field of solar cells, by academics working in various institutes (e.g. Fraunhofer Institute in Freiburg and ISET in Kassel). In the US, public laboratories pursue basic research, and are similar to academic departments in many ways (Bozeman, 2000). If we are to assess the competence base which lies beyond industry, and which may be a source of both new technology, trained people and firms,[17] we ought not to leave these parts of the 'non-business' R&D sector out of the analysis.[18]

Unfortunately, available data do not cover many countries but a comparison can be made with both Germany and Japan. Academic R&D in Science and Technology as well as total R&D (in Science and Technology) in academia, government and institutes are set out in relation to GDP in table 1. We can observe that Sweden greatly outperforms the other two countries in terms of academic R&D. However, the picture alters if we also include R&D carried out in government and institutes. Indeed, Japan performs better and Germany is very close to the Swedish position. The picture of the superior strength of Swedish ‘non-business’ R&D largely disappears.[19]

Table 1

R&D in Science and Technology per GDP in academia and outside industry in Sweden, Germany and Japan, 1995

Country	R&D/GDP in academia	R&D/GDP outside industry*
Sweden	0.0061	0.0072
Germany	0.0033	0.0064
Japan	0.0039	0.0078

* R&D undertaken in academia, in institutes, and in government

Source: Elaboration on OECD (2000), table 7 and OECD (2000a), Annexe 1A.

Methodological problems also exist in the interpretation of *publication* data. The bulk of Swedish publications (about 85 per cent, see Vinnova, 2001) refer to the life science field while other fields are less strong. This dominance reflects a societal choice to enhance the knowledge base of the health care system, but it is also a reflection of the requirement of writing a thesis, with associated publications, for doctors to be promoted to consultants. Hence, the learning process of doctors is reflected in published articles, which is not the case in many other countries, e.g. Britain. We may therefore, and this is the first problem, reduce the Swedish figures accordingly.

A second problem lies in the existence of an English language bias in the journals employed to build up bibliometric databases. This bias can be strong, indeed as much as a 50 per cent increase in the propensity to publish can be seen in countries which have English as the first language (Pavitt, 1998, citing Lattimore and Revesz, 1996). English is, of course, not the first language in Sweden, but the small northern European countries simply have to adopt English as a working language due to a small domestic 'scientific market'. This means that Swedes are expected to be more likely to publish in the English language journals than researchers from larger, non-English speaking countries. We would therefore expect that an English language bias applies to a certain extent to the Swedish data. Both these factors exaggerate the Swedish strength, although by how much is not possible to say without further enquiries. A brief comparison with Germany may, however, be suggestive. As mentioned above (table 1), the Swedish and German R&D/GDP is broadly the same if we include R&D undertaken in institutes and government, but in terms of number of publications set in relation to GDP, Sweden is nearly twice as 'productive' (Henrekson and Rosenberg, 2000, figure 3.1). Unless we have good reasons to expect that Swedish scientists are superior to the German (which seems difficult to argue), a reliance on publication data would be dangerous.

Much of the discussion on industry-academia relations implicitly refers to the *engineering* field. This *provides the knowledge base for the bulk of new start-ups* (Rickne and Jacobsson, 1999) as well as for the *bulk of the high tech industry* (Jacobsson et al., 2001) (with the exception of the pharmaceutical industry).[20] Scrutinizing publication data for the engineering sector, (table 2), we can discern the strength of Swedish academia, but, again, Sweden is not so outstanding as might be thought at first glance. Indeed, in terms of numbers of publications per capita, Sweden is one of several countries in a group that trails behind Israel (and at about the same level as Canada, Finland, Switzerland and the UK).

Table 2

The relative strength of Swedish engineering research, as measured by number of published articles (1994-1998) divided by (million of) population (1997)

Country	Total	ICT**	Biotechnology*
Israel	891	223	24
Switzerland	836	154	51
Sweden	768	125	40
Canada	723	157	35
Finland	644	132	37
UK	634	135	32
Netherlands	572	115	38
US	559	131	16
Australia	543	111	20
Denmark	461	87	46
Belgium	444	108	26
Japan	416	95	19
France	412	75	24
Germany	398	69	17
Austria	352	58	25
Italy	271	68	9

* including molecular biology
** includes ‘Computer Science & Engineering’, ‘Electrical & Electronic Engineering’ and ‘Information Technology & Communications Systems’

Source: Bibliometric data on the number of articles published per country was kindly made available by Dr. O. Persson; Population data was taken from OECD (2000).

Looking at Sweden’s performance in separate knowledge fields within engineering, we can note that Sweden ranks only no. 9 in Computer Science & Engineering[21] and no. 7 in ICT in total.[22] The late build-up of Swedish research (the expansion in the number of professorial chairs started only in the second half of the 1980s (Jacobsson, 1997) obviously still plagues the area in Sweden. Curiously enough, it is in ICT that Swedish industry gained a very strong position in association with the expansion of the mobile telephony sector in the 1990s. Indeed, two out of three patent classes where Sweden increased its share of world patenting in the 1990s as compared to the 1980s, were in ICT, medical electronics and telecommunications (Persson, 2000, table 10); the trade performance is impressive and the number of start-ups in mobile internet is very high. *The case of ICT clearly then exhibits signs of a technological and industrial success (so far) in spite of a relatively weak university sector, i.e. a situation which is the opposite of that portrayed in the literature referred to above*!

In biotechnology (including molecular biology), Sweden ranks as no. 3 but the next three countries are close behind. In terms of start-ups, patenting and trade, there is a lot which points to good performance. Although it is difficult to clearly define the borders of a biotechnology, available evidence suggests that Sweden has a fair number of start-ups (Vinnova, 2001); Sweden increased its share of world patenting in pharmaceuticals in the 1990s (although not in biotechnology, see Persson, 2000), and the industrial and trade performance is very impressive.

In conclusion, there are important methodological issues involved in measuring the strength and performance of the academic sector, problems that would appear to have exaggerated the relative strength of R&D undertaken in Swedish academia. There are also problems involved in relating the performance of academia to a set of indicators of a supposedly poor industrial transformation (in this case number of start-ups and the production and trade performance of the high tech sector). *The case for focussing on a poor exploitation of academic research in Sweden does not seem as strong as may be thought at first glance*.

Yet, that literature has pointed us in the direction of analysing governance and incentive structures and how they influence the functioning of the innovation system. In spite of the discussion above, it is clear that the generation and exploitation of knowledge in biotechnology and in pharmaceuticals is not without problems in Sweden. Indeed, the study by Rickne (2000) suggests that there is room for much improvement in the Swedish technological system for biomaterials, as does the evidence massed in Carlsson (2002) and by Vinnova (2001) for biotechnology in general. Nor do we argue that there is not room for improvement in the electronics sector. Indeed, as was shown above, and which will be elaborated on below, Sweden's academic response to the opportunities in ICT was late in terms of developing the required capabilities. But rather than match data on academic input and output with indicators of industrial transformation, with results which are difficult to interpret, we suggest that it would be more useful to learn about how capabilities are formed in the academic sector and how these are exploited (if at all) through various mechanisms and in different knowledge fields, as discussed in section two (and as suggested in section six).

Science policy shapes the formation of these capabilities. In the next section, we will discuss how a range of sources of uncertainty makes it very hard to assess the value of academic R&D and what risks there may be with a policy that emphasises 'demonstrated applicability'. In section five, we will deal with the 'responsiveness' of academia to new opportunities. Part of that process is influenced by governance structures, and incentives associated with these.

4. Assessing the value of academic R&D

4.1 Introduction

There is a growing pressure for 'accountability' in the public funding for academic R&D (Pavitt, 2001; Geuna, 2001; Benner and Sandström, 2000). Scientific benefits of research need to be supplemented with an identification of possible practical benefits and academia is encouraged to, and forced to, work with, and gain funding from, industrial partners. Accountability necessarily involves showing convincing evidence of the benefits of R&D. This can be done either ex-post, where benefits are demonstrated for R&D that has already been carried out, or ex-ante, which involves an assessment of the future benefits of R&D.

There are very considerable problems concerned with measuring benefits in ex ante evaluations. Evaluations that attempt to assess the 'usefulness' of the R&D in terms of applicability, necessarily run up against a whole set of problems with respect to uncertainties related to both technology and markets. These uncertainties will be largely resolved by the time an ex-post evaluation takes place, although this is dependent on the time scale involved in the evaluation process. In this section, we will discuss both cases, beginning with the ex post case. A greater emphasis will be put on the ex-ante case, given its greater relevance for the current debate,

4.2 Measuring the usefulness of science 'ex-post'

A large literature has tried to measure the usefulness of science, ex-post. Many different methodological approaches have been used:[23]

- Production functions (e.g. Autant-Bernard, 2001),
- Counting spin-offs (e.g. Rickne, 2000, Lindholm-Dahlstrand, 1999),
- Bibliometric and patent analyses (e.g. Godin and Gingras, 2000; McMillan et al. 2000, Hicks et al., 2001),
- Interview techniques (e.g. Faulkner and Senker, 1994),
- Questionnaire (e.g. Mansfield and Lee, 1996)
- Cartography (Sörlin and Törnkvist, 2000).

Given our broad framework it comes as no surprise that, methodologically, it can be expected to be extremely difficult to trace the impact of academic research on industry, i.e. to make an ex-post evaluation of academic R&D. Clearly, the benefits of academic research cannot be measured using one or two mechanisms but need to cover all mechanisms. More importantly, the often indirect and subtle links between academic R&D and industry create very considerable problems for tracing the benefits of an interaction. For instance, how can the importance of sharing tacit knowledge through informal networks be assessed? How can we trace the impact of research on industry through the quality of undergraduate and graduate training? Not only is measurement extremely difficult but the contribution to functionality and the mechanisms through which these benefits may accrue to industry clearly vary between knowledge fields which means that, as Salter and Martin (2001, p. 527), put it: "… no simple model of the economic benefits from basic research is possible…"

Furthermore, the time frame involved in retrospective studies may be very long indeed, and the judgement of the success or failure of a particular research programme may well depend on the specific time frame used. For instance, the German Federal Government spent 2 billion DM on solar cell research, primarily at universities and institutes between 1975 and 1999, but the German stock of solar cells was only 67 MW in 1999 (Jacobsson, et al., 2002). Is this a failure or do we need to wait another

10 or 20 years before we evaluate (anything else in this case would be unreasonable)? Clearly, the cut-off point may have a decisive impact on the outcome of an evaluation.

The time scale involved presents us with an additional methodological problem, namely if we are to understand the role of universities in the formation of new innovation systems, we are speaking of mapping processes which span over decades and where (as mentioned above) the mechanisms involved are many and difficult to trace. Methodological ingenuity and pluralism is, therefore, required in a study of how universities influence technical change.

4.2 Measuring the usefulness of science ‘ex ante’

It goes without saying that there may be large uncertainties of a technical nature in a R&D project. We will not focus on such uncertainties but rather on those that remain after the new knowledge is transformed into an innovation (when it is first applied), uncertainties which need to be resolved if we are to expect any sort of conventional ‘rationality’ in measuring the usefulness of science ex-ante. Inspired by Rosenberg’s (1996) superb article on ‘Uncertainty and Technological Change’, we will discuss a set of sources of uncertainties which may lead to an inability to anticipate the future impact of an innovation and, therefore, of estimating the social value of the research leading to that innovation. There are at least four such sources which need to be considered.

First, the innovation often has a poor price/performance ratio and it takes a whole series of ‘secondary’ innovations (Schmookler, 1966) to make it suitable for various applications. However, initial poor performance properties may be such that it is not obvious where these applications would be. There are a large number of anecdotes revealing a fully justifiable narrow view of the potential of a new technology. For instance, Marconi, who invented the radio, did not see it as an instrument of broadcasting but one of point-to-point communication where wired communication was not possible (Rosenberg, 1996). These problems are compounded by the fact that many applications eventually turn out to be in a different industry than that which originally applied the new technology. For instance, the steam engine was for a long time considered exclusively as a pump, as it was invented to drain flooded mines

(Rosenberg, 1996). The inter-sectoral diffusion is, of course, extremely difficult to predict, as the case of laser clearly demonstrates, with an ever-widening area of application over a period of more than 30 years.

A recent case in point is computer science, as revealed in the excellent study on government support for computing research in the US (Computer Science and Telecommunications Board, 1999, 150-151) and which is worth quoting at some length:

"Scientific and technological research explores the unknown; hence its outcomes cannot be predicted at the start - even if a clear, practical goal motivates the work. In fact, outcomes anticipated at the start of a research project can differ from those eventually achieved or that prove to be most important. The Internet is a case in point. DARPA's early interest in packet-switched networks…grew from a desire to use more efficiently the computing capabilities that were distributed among its many contractor sites. By allowing remote access to these disparate computers in a seamless fashion, DARPA program managers hoped to expand the number of researchers who could use them and increase their utilization rates. These results were achieved in the end, but, as the ARPANET was subsumed into the NSFNET, which later evolved into Internet, the range of applications for packet-switched networks expanded in a number of unanticipated directions. Few could have predicted the popularity of electronic mail as a means of communication…still fewer could have anticipated the emergence of World Wide Web…"

Second, uncertainties with respect to the future impact of an innovation, arise from the emergence of other innovations in the form of competing designs (Utterback, 1994) as well as from improvements in existing technologies (Rosenberg, 1996). It is extremely difficult to correctly forecast which competing design will eventually dominate the market, and uncertainties may prevail over a long period of time. For instance, in the case of solar cells, crystalline silicon cells have been challenged for more than a decade by amorphous silicon, cadmium telluride and copper-indium-selenide cells. Science policy makers have had to accept that they cannot predict which of these will dominate, and funding is now given to a variety of design approaches (Jacobsson et al. 2002). It is even more difficult to know whether or not any of these design approaches will eventually out-compete the incumbent crystalline silicon cells, as much effort is being mobilised to improve its price/performance in the face of competition by these designs.[24]

Third, rarely is a new technology useful on its own but requires the development of complementary technology(ies). For instance, the use of fibre optics in telecommunication required the development of laser technology (Granberg, 1988). Indeed, major technological innovations, i.e. ones which have, in the end, a very high social value, often form a vital part of a new technical system comprising a whole range of technologies which need to evolve for the value of the initial innovation to materialise.

As mentioned above, the time scale involved in the whole process of diffusion may be very long. This is especially so when whole new technical systems are concerned (Rosenberg, 1996) – it took, for instance, many decades to develop all the applications for electricity after Faraday discovered electromagnetic induction in 1831 (Rosenberg, 1996) and fifty years after the first computer, we are still not at the end of the ICT revolution. A lengthy period between an innovation and its full impact is also common at the level of the individual innovation. The first solar cell was developed in the 1950s and yet the diffusion process has only just started (Jacobsson et al., 2002). The first numerically controlled machine tool was produced in the mid 1950s, while a large-scale diffusion (after a number of secondary innovations particularly related to ICT) only began in the second half of the 1970s (Jacobsson, 1986). The competence base in microwave antenna technology in Western Sweden began to develop in the 1950s, driven by the needs of Onsala Space Observatory, but the economic returns only began to come in the 1990s when the knowledge base could be exploited in the booming mobile telephone business. This application was not, of course, perceived in the 1950s and was, again, dependent on a whole range of complementary innovations in ICT (Holmen, 2001).[25]

Fourth, a further complicating factor for policy makers is that the economic benefits of academic R&D that accrue to the national, or regional, economy depend on the functioning of the entire technological system. This introduces yet another uncertainty where it is quite plausible that high class academic R&D is pursued in a knowledge field for which the receiver competence of industry is underdeveloped (Salter el al., 2000), or where the incentives for, or interest in, exploiting the new technology are poor (Henrekson and Rosenberg, 2000). The economic benefits of academic R&D may therefore not materialise, or may do so abroad.

This is clearly the case of Swedish academic research in some renewable energy technologies, which so far has found little application in Sweden for reasons found outside of academia (Johnson and Jacobsson, 2001). Again, it is hard, or even impossible, to predict the evolution of the technological system,[26] in part because serendipities abound here. For instance, in the case of microwave antenna technology referred to above, Ericsson's decision to move a factory for military electronics to Gothenburg (in part to get it as far away as possible from the threat of Russian bombers) was a crucial step in forming a local technological system, which eventually became very successful (Holmen, 2001).

Uncertainty goes, therefore, far beyond technical feasibility at the level of an individual invention. Indeed, the use of the term uncertainty may not be fully appropriate. A more appropriate term is 'ignorance' as decision makers simply cannot have access to either the full range of potential outcomes, or the probability distribution with respect to those which can be identified (Rosenberg, 1996). In a situation of ignorance, quantifying the expected benefits of academic R&D *does not seem to be possible* and, hence, there is no reason to believe that choice can be 'rational' (Rosenberg, 1996, Computer Science and Telecommunications Board, 1999).

Another, and more promising, way of thinking about the value of research is that it generates options (Scott et al., 2001). Clearly, science generates options in the form of new knowledge, but as argued above, the value of such options cannot really be expected to be ascertained, even in terms of orders of magnitude. Instead, in an uncertain and complex world, the main justification for academic research would instead lie in *building capabilities, which embody the ability to generate, and eventually, to contribute to the realisation of (some of) these options, most of which are unknown at the point of decision to develop a capability, but some which can perhaps be imagined.*[27] As Loasby (1998, p. 144) argues:

" Capabilities are the least definable kinds of productive resources. They are in large measure a by-product of past activities, but what matters *at any point in time is the range of future activities which they make possible*. What gives this question its salience is the possibility of shaping capabilities, and especially of configuring clusters of capabilities, in an attempt to make some preparation for future events, which, though not predictable, may…be imagined" (our italics)

The main benefit of science is therefore that it generates capabilities so that society can create and respond to new opportunities; i.e. support for academic research is, as Salter and Martin (2001, p. 528) put it: "…an investment in a society's *learning capabilities*." *This is why it is so important to integrate PhD education with research and this is why research should also be integrated with advanced undergraduate education*.[28]

This is also why, as Pavitt (2000) phrases it: 'good science is useful science'; capabilities generated through pursuing good science are socially useful. The US achievement in science-based technologies is partly based on research and institutions that are ranked highly by pure academic standards (Pavitt, 2001, p. 19), where first class capabilities are generated. [29]

The main challenge for Science Policy is to make sure that capabilities are built in terms of volume, variety and quality. Failing to meet this challenge will imply that the profitability of firms' investment in R&D will be adversely affected. The current emphasis on demonstrated applicability and commercial value of research[30] risks not only to be at odds with the fundamental uncertainties of the innovation and diffusion process, but may also lead to a Science Policy which may not manage that challenge.[31] It is easy to point to three real risks involved in demanding that applicability should be demonstrated (i.e. of a science policy with an emphasis on short term usefulness in terms of the codified information coming out of research).

First, incremental improvements, and applications of what already is known, would exhibit lower uncertainties and it would, therefore, tend to be easier to pinpoint its benefits than the expected benefits of ventures into the truly unknown. Knowledge production and the associated training of PhDs, i.e. capability generation, may therefore become biased in favour of less path-breaking work, i.e. in that process, the *quality* of the capabilities may suffer.[32]

Second, given the uncertainties discussed above, rigorously applied, a demand for applicability would mean that capabilities in new fields, with gestation periods of decades, simply would not be developed, i.e. Science Policy may fail to deliver in terms of *variety.*

Third, taking ‘demonstrated applicability’ to the extreme, may lead to a selection of ‘bad science,’ which is pursued in the ‘right’ area and such science is, of course, useless.

The emphasis on ‘demonstrated applicability’ thus risks biasing the capabilities formed at the expense of quality and variety. The dangers to society are multiplied by the expectation that the ability of academia to contribute to society in all remaining mechanisms (see section 2.3) is dependent on the quality and variety of the capabilities generated.

5. Improving the value of the academic sector; ‘responsiveness’, science and educational policy and governance structures of the university sector

A science policy where the generation of capabilities is the central issue, needs to be concerned with the speed and strength by which universities explore new fields. The ‘response’ capacity has implications not only for the generation of specific options and capabilities in the form of e.g. PhDs, but also for the ability to develop new undergraduate programmes and to expand them as and when a new knowledge field has matured enough to be applied widely in society. We will first discuss this capacity in research and then turn to the education of engineers and scientists. In doing so, we will elaborate on the challenge of science and educational policy to build capabilities in terms of volume, variety and quality.

a) ‘Responsiveness’ in research

In the Swedish case, one can point to both ICT and to biotechnology as cases where a response capacity did not develop as one might perhaps have wished. Indeed, in the 1970s and 1980s, an external agent, the Swedish Board for Technical Development

(STU), intervened in the research systems of ICT and genetic engineering. STU played a major role in developing these new knowledge fields by financing new professorships and graduate programmes (Jacobsson, 1997; Carlsson and Jacobsson, 1997; Vinnova, 2002).

Achieving a high degree of responsiveness in research – i.e. maintaining or increasing variety and increasing volumes in new knowledge fields - may be obstructed by a whole range of factors, residing both outside of and within the universities. We may point to five reasons.

First, new professorships (with governmental funding) have always been created by the government. This has made the development of a new knowledge field highly dependent on the perception of the future (how the future is imagined) among a limited number of policy makers and bureaucrats.

Second, as argued by Benner and Sandström (2000), where scientists dominate a research-funding organisation, these may simply not accept competition from a new scientific area. In biotechnology, Benner and Sandström (2000) point to the reluctance of the traditional research councils (with the exception of the Engineering Science Research Council) to fund work in this new field and it was largely up to a new Strategic Foundation (and to NUTEK, formerly STU) to build the new field.

Third, industry may not act in favour of research in areas which have little relevance for their *current* business. Present activities constrain how the future is imagined with the consequence that current dominant industrial sectors may shape the capability generation in a conservative way. Granberg and Stankiewicz (1981, p. 51, our translation) wrote 20 years ago about new technologies such as enzyme technology, genetic engineering and microelectronics:

"Nothing has been revealed in our study which points to industry pressing these cases…one is struck in this context by the inertia by which the electronics related base technologies were introduced into the Swedish higher educational system. Today, industry is very conscious of the unfortunate in this development."

A more recent example is that of the Internet, where a recent study concludes that (Odhnoff and Hamngren, 2002, p. 5, our translation):

"If KTH and the other technical universities had waited for the leaders of the Swedish telecommunications industry to wake up to the importance of Internet, Sweden would have definitely lagged behind. Now there was a response to what was happening in the US, which gave a reasonable point of departure when the Swedish telecommunications industry belatedly jumped on the Internet bandwagon."

Fourth, factors within the universities may contribute to inertia. When research is fully 'curiosity driven,' it is to be expected that researchers, of some standing at least, follow international scientific trends. However, for various reasons management may not be able to expand research very forcefully into new fields. For instance, for internal 'political' reasons, it may prolong the life of outdated knowledge fields. There may also be obstacles to developing technologies that rely on an integration of organisationally separate knowledge fields. A more important reason today, however, is probably that management has very little resources to play with, of which much is committed to supporting undergraduate and graduate teaching in useful knowledge fields.

Take the Swedish case, where only about one third of the research funds in technical sciences come in the form of fixed funding (SCB, 2001, table 10). These resources are supposed to cover essential research needed to support teaching, by both lecturers and professors; the cost of teaching PhD students and the cost of PhD students taking courses (PhD students in the technical sciences in Sweden are normally paid a proper salary and along with these come all sorts of overhead costs).

A rough calculation suggests that the fixed funds given to the technical sciences cover these costs, but not much more.[33] Of the 1 152 million SEK received in the form of fixed funding less than 400 remained for research which went beyond supporting teaching. This sum should then be set in relation to the external funding of over 2 billion SEK (SCB, 2001, table 10). Hence, the freedom to manoeuvre for management is probably very limited. Indeed, the paucity of fixed funding might even limit the ability of the universities to respond to international scientific trends without relying on the funding decisions of external actors.[34] To the extent that these are limited in their images of the future, for instance by relying too much on the expressed demand from dominant industrial businesses, a slow response to international scientific developments may occur. This suggests that, today, an analysis of responsiveness and inertia must include the functioning of external funding agencies (and how they imagine the future) and this is the fifth source of inertia.

In the Swedish case, a smaller sum (258 million SEK in 1999, see SCB, 2001, table 10) was available from the Swedish Research Council for Engineering Sciences, which is a traditional peer-controlled research council. Many (or most) of the remaining funders are concerned with the applicability of research. Apart from the European Union and firms (together 405 million SEK), substantial funds are contributed by NUTEK, Vinnova and the Foundation for Strategic Research. NUTEK was the largest funder of technical research, but after a reorganisation in the mid 1990s, it lost one third of its resources and it has moved to finance near market R&D (Benner and Sandström, 2000). Yet more resources were lost when a new organisation, Vinnova, was recently founded, financing 'user motivated research and development'. Finally, the Foundation for Strategic Research was founded in 1993, which combines a selection of knowledge fields with good prospects for industrial applications (e.g. microelectronics and combustion science) with the funding of graduate schools, i.e. it funds PhD research in selected fields (Benner and Sandström, 2000). Whereas the emphasis on applied work is not in itself a problem in the technical sciences (as will be argued more below), the strong bias in favour of external funders raises fundamental questions about how knowledge fields are selected and, as a consequence, how the quantity and variety of capabilities are shaped. It also raises questions about the selection of problems to be researched and the quality of the capabilities.

Of course, these five potential sources of inertia do not work independently but would be expected to tend to reinforce each other. This would suggest that agents which are not only external to the universities and the traditional science councils (which is the common argument), but which also, to a certain extent, act *independently of current dominant industrial businesses* may have a key role to play in creating a 'responsiveness'.

A case in point[35] is the research programme ‘Digital Communication’, which started in 1987, as a part of a very large technology policy programme in ICT. It built on earlier smaller programmes in digital radio technology but in the early 1980s, industry (i.e. Ericsson and Telia) feared that the knowledge base in digital communication would be too small to support industry in the second generation mobile telephony which they knew would be digital. Industry, academia and STU (the predecessor of NUTEK) had intense consultations where for instance, the Director for Research of Ericsson Radio Systems wrote in 1987 (Vinnova, 2002, p. 20, our translation):

“The second generation mobile telephony will be digital…Sweden is playing a leading role in this development…for Ericsson Radio System it is vital that STU give priority to a framework programme in digital mobile radio.”

The programme combined scientific excellence with an orientation towards a broader knowledge field in which a small but expanding part of Swedish industry (otherwise dominated by mechanical engineering) articulated a need for PhDs with capabilities which could be employed to develop systems according to GSM standards. As fresh funding was made available, and an initial competence had earlier been built up on a smaller scale, universities responded quickly by expanding PhD education in this field.

The US experience also clearly suggests that massive government support to develop a specific (targeted) new and broad knowledge field can be very successful. Federal support was, for example, exceedingly important for the development of the computer science field. In a study cited above, this support was summarized as follows (Computer Science and Telecommunications Board, 1999, p. 136):

“…federal support has accounted for a substantial fraction of the total funding for computing research …and the vast majority of all university research funds in the field. Such funding has supported both the development of new technologies and the training of students. The federal government has also paid for public research infrastructure, providing most of the funds for research equipment in the university department of computer science and electrical engineering, and has sponsored programs to provide access to and infrastructure for high-performance computing and networking.”

The success lies not only in the early timing and the large amounts of funding but also in *how the support was given.* Two lessons are especially pertinent in this context.

First, the programme managers had a 'light touch' in that they did not select specific R&D problems to be pursued by academia:[36]

"This style of funding and management resulted in government stimulating innovation with a light touch, allowing researchers room to pursue new areas of enquiry" (ibid, p. 11) and "This reality counters the myth that government bureaucrats heavy-handedly selected R&D problems…" (Ibid, p. 102).

Second, handling the inherent uncertainties in an evolving new field (see section 3) required high competence and flexibility from funding organisations:

"Researchers need sufficient intellectual freedom to follow their intuition and to modify research plans based on preliminary results. Constraining research too narrowly can limit their ability and willingness to take risks in choosing new research directions. Building such flexibility into federal structures for managing research requires both skilled program managers – who understand, articulate and promote the visions of researchers – and an organizational culture that accepts and promotes exploratory efforts (ibid, p. 151).

Hence, targeting the new broad field was combined with a great deal of intellectual freedom; *applied work should therefore not be confused with 'demonstrated applicability.'*

Indeed, practical concerns, but not always those of immediate relevance to industry today, clearly often guide academic research. As Rosenberg and Nelson (1994, p. 332, 340) argue:

"…a widely accepted definition of basic research has come to focus on the absence of concern with practical applications rather than the search for a fundamental understanding of natural phenomena. This is unfortunate, indeed bizarre…we do not mean that such research is not guided by practical concerns…it is a gross misconception to think that if research is 'basic' this means the work is not motivated by or funded because of its promise to deal with a class of practical problems. Nor does it mean that university scientists and engineers are not building and working with prototypes of applicable industrial technology. Indeed this is a central part of academic research in many engineering fields."

The motivation to solve practical problems cannot be seen better than in institutes of technology (e.g. MIT and NJIT in the US, Chalmers and KTH in Sweden), which were built up to support industry and where undergraduate and graduate education is closely linked to industry. This is evident simply by looking at the names of the various departments (e.g. energy technology, combustion engineering etc) and how these have changed over the years. Granberg and Stankiewicz (1981, p.21) clearly point this out when they suggest, " as a reasonable generalisation, it can be said that the needs of industry strongly guide the creation and orientation of new engineering departments (our translation)". [37]

In the Swedish context, the applied nature of the science base is especially pronounced where the combined share of engineering and medicine (also very concerned with solving practical problems) is particularly high (Pavitt, 2001). The perception of what engineering schools, and probably schools of medicine, do, as well as their degree and types of interaction with industry, seems to be somewhat at odds with that in the 'triple helix' literature. For instance, Benner and Sandström (2000, p. 293) summarize that perception as follows:[38]

"The academic system focussed on fundamental research, organized along disciplinary boundaries, and had only limited and mediated contacts with politics and industry…now with the second industrial revolution…academic research is pursued with openness towards practical applications and commercial exploitation of academic research".

However, whereas much academic work is applied, given the range of sources of inertia listed above, a considerable space in the funding system is justified for organisations which assemble and articulate needs from emerging segments of industry for new capabilities. A substantial share of directed research is therefore a necessary and useful element in a Science Policy[39], but only *as long as it is directed towards newer and broadly defined fields and it is combined with high scientific standards and the development of capabilities at the doctorate and other levels.*[40]

b) ‘Responsiveness’ in terms of education

The Swedish higher educational system (HES) used to be highly centralised where the Department of Education controlled the volume and orientation of undergraduate education in great detail. For instance, when Chalmers University of Technology wanted to start a course in Computer Science, they had to apply for permission from, and bargain about funding with, the Department of Education. Since the early or mid-1990s, central government only controls the volume of education by allocating a number of student places to each university. These may then reallocate the places between various subjects. This has opened up the possibility for a university to develop new fields without any central approval.

Yet, a restriction on the total number of student places sets a de facto restriction on local flexibility, as an expansion in one field will have to be made at the expense of another field. For instance, an excess demand for engineers with a knowledge in microwave technology has existed for some time in Western Sweden, but if the School of Electronics were to have satisfied this demand, it would have led to a sharp reduction in the graduation of electronics engineers with other specialities, or to the reduction in the supply of engineers in computer science or mechanical engineering. This meant that a ceiling on the number of students learning microwave technology was set, a ceiling which was far below the demand for such engineers in the region (Holmen, 2001).

In other cases, new degrees have been implemented at the expense of ‘old’ areas. One example is ‘technical design’ which was developed at the expense of study places in mechanical engineering. An improved opportunity, although still *constrained*, thus exists to develop new degrees. This situation could be contrasted with that in the US, which is characterised by decentralisation and an autonomy to act, which is likely to lead to a greater ability to balance demand and supply (Henrekson and Rosenberg, 2000).

Henrekson and Rosenberg (2000) also point to the dangers of the Swedish practice of separating research and undergraduate education, which has probably led to a slower incorporation of new findings into teaching. This is extremely important as, as was argued above, one of the main mechanisms by which research affects industry is through teaching at various levels. Indeed, ensuring that researchers are involved in undergraduate and graduate education is, therefore, of fundamental importance.[41]

The responsiveness of the whole university system is, however, not only dependent on the balance between centralised and decentralised decision making, or to factors within a specific university. Take the case of education in ICT in Sweden where a poor responsiveness could be easily discerned, at least compared to the US (Jacobsson, 1997; Jacobsson et al., 2001). In Sweden, the number of electronics engineers and computer scientists graduating per capita (at the BSc and MSc levels), was well below that of the US until the mid 1990s, and there was a persistent excess demand for study places. Whereas Henrekson and Rosenberg (2000) attribute this pattern, in a convincing way, to the greater decentralisation and to a different incentive structure in the US, Jacobsson et al. (2001) also point to the *structure* of the Swedish HES until the 1990s as an important explanatory factor. Sweden's 'catching-up' in the mid 1990s was primarily[42] due to the introduction of a two tier educational system in Sweden, which expanded access to higher education very significantly. Such a system has long been in place in the US, while in California, there is even a three tier one (Carlsson and Jacobsson, 1997).[43]

Yet a third factor to consider is the role of agents, external to the university. We saw above the central role played by the Federal Government (in part channelled through the Department of Defence), in building up the whole knowledge field of computer science in the US, thereby enabling *an early start in teaching* in that field (Rosenberg, 2000). Hence, in seeking explanations to varying degrees of 'responsiveness', it is not only governance forms that appear to matter but also how the non-market based educational system is dimensioned and structured as well as the role of external agents in building up competence in new fields.

Finally, as would be expected in an innovation system approach, it would be a grave mistake, particularly in the engineering field, to neglect the influence of timing, and the strength with which industry articulates its demand for new educational orientations (and volumes of graduates). As Granberg and Stankiewicz (1981, p.47) point out, "The present or expected demand from industry of engineers with certain competence profile controls in an obvious way the creation of new Chairs…However, it is a matter of control which primarily affects the educational functions."

A poor responsiveness could, therefore, be contributed to by industry, if it fails to articulate a demand for new competence in good time. Clearly, one may imagine a situation where a failure by the current industry to articulate the needs of the industry of the future exacerbates other causes of inertia resulting in a vicious circle. Sweden was probably a case in point in the 1970s and 1980s in the field of electronics and computer science (Jacobsson, 1997). *A poor responsiveness would in such a case not be defined in relation to the needs of current industry but in relation to growing scientific and technological opportunities* and the universities would need to act in a proactive fashion and *not only respond to the expressed needs of dominant industrial actors.*

6. Suggestions for further research

In this final section, we will outline some suggestions for further research. We will start with a brief summary of our findings for science policy and continue with the contours of a large and internationally comparative project, which may incorporate many of the issues identified in the text. We will then point to a set of questions that can be carried out on a smaller scale but which could also form part of the larger project.

An appropriate science policy rests on an understanding of the following points that have emerged in this selective review:

- A justification of academic R&D which is based primarily on the appreciation of the key role of the generation of capabilities, and that the main challenge for science policy is to make sure that capabilities are built in terms of volume, variety and quality
- That high scientific standards and intellectual freedom are a prerequisite for, and not an obstacle to, a rich relationship between industry and academia

- The dangers of biasing the formation of capabilities by emphasizing 'demonstrated applicability' and immediate commercial value
- The role played by the other parts of the technological systems (e.g. the existing industry, venture capital firms, prevailing culture, external funding agencies) in shaping and exploiting these capabilities
- The diversity of patterns of interaction between universities and industry, including the determinants of that diversity. In particular, science policy needs to grasp the importance of less visible (and more difficult to measure) mechanisms so as to generate a complete picture of how universities contribute to functionality. In this connection, it is necessary to distinguish between universities of technologies and other universities.
- The range of determinants of the responsiveness of universities in terms of both research and education, including the usefulness of various governance forms, the existence and behaviour of various external funding agencies and the role of industry.
- That a substantial share of directed research is a necessary and useful element in a science policy, but only as long as it is directed towards newer and broadly defined fields and it is combined with high scientific standards and the development of capabilities at the doctorate and other levels.

In order to improve our understanding of many of these points, we can envision a large internationally comparative project analysing

a) the evolution of specific but broadly defined knowledge fields (e.g. computer science) in both research and education, b) the interaction of universities with industry through all kinds of mechanisms in these fields (including an analysis of obstacles to the proper functioning of each mechanism), c) the determinants of these patterns, be they in the form of virtuous or vicious circles, including both governance structure of the universities, the nature of science policy, the existence and behaviour of external actors funding research and the nature of the remaining components of the surrounding technological systems. The scope of the study can vary with regard to the number of a) knowledge fields, b) countries (and universities in each country) and c) mechanisms.

A project of that nature would be ambitious and costly and would have to be undertaken with different national teams using their knowledge of their respective home bases. A way to start off such a project would be to pursue a couple of pilot projects where the focus would be on knowledge fields of which we already have a good overview of the respective innovation systems, knowledge which is hard to come by. Examples of such knowledge fields are renewable energy technologies, telematics and biotechnology. We could then analyse these at the national or regional levels, where the analysis runs through the three stages mentioned above. This is feasible and we would probably learn much for the design of a larger project.

In addition, we can point to a set of smaller projects which would be very useful to pursue.

1. Whereas great progress has been made in terms of R&D statistics and bibliometrics, there are still some *methodological problems to tackle in cross-country comparisons* of the strength and performance of research undertaken outside of industry. More specifically, we are not certain of the magnitude of the methodological problems pointed at in section 3.

2. In a situation of ignorance about future applications of technology and its value, there is no reason to believe that choice can be 'rational'. In an uncertain and complex world, the main justification for academic research would not lie in the production of information in the shape of a public good, but instead lie in building capabilities. *Further work is required to develop a capability-based rationale for funding of academic research.*

3. Given the inherent impossibility of demonstrating applicability in more than a very general sense, how is 'applicability' used by Science Policy makers to select *areas* for funding and for screening *projects*? There are two issues which need further elaboration. First, to what extent does the selection reflect the need of the present dominant industrial businesses (with the risk of repeating the historical mistakes in biotechnology and electronics), and to what extent does it reflect the need of capabilities in emerging business areas, i.e. what is the balance between satisfying

demand from current activities and funding capabilities in exciting, but highly uncertain, new areas? Second, to what extent are capabilities generated in a context of intellectual freedom and to what extent is academic research steered towards specific questions and towards product development? In the latter case, it would be useful to analyse the potential risks involved in (mis)shaping the capabilities by placing too great an emphasis on ‘demonstrated applicability’. *Case studies of management of different external funding organisations would seem appropriate. These may span over the range of funding agencies, which now exist in Sweden.*

4. What is the political economy of the ‘cry for demonstrated applicability’ when it has been shown that a) an ex-ante evaluation of the applicability is hardly possible, except for, perhaps, incremental innovations, and b) ‘good science is useful science’? *It would be useful to learn which interest groups have shaped the agenda, the perceptions of the innovation and growth process of these groups, and related to this, what is the empirical substance behind the claim that universities, in particular universities of technology, used to have little contact with industry? Little is gained from analyses, which fail to understand the differences between universities of technology and traditional universities.*

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[1] The ‘innovation process’ includes the diffusion of technology.
[2] See also Meyer-Krahmer and Schmoch (1998) on this point.
[3] This paragraph, and the two following, draw heavily on Johnson and Jacobson (2001).
[4] Rickne (2000) provides us with a more detailed set of functions.
[5] Indeed, as pointed out long ago by Myrdal, these virtuous circles are central to a development process - as these circles are formed, the evolution of the technological system begins to be self-sustained. He even suggested that (Myrdal, 1957, p. 18) “ the main scientific task is…to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes”.
[6] Take, for instance, the current debate over which policy structure is the most appropriate to promote renewable energy, where the proponents of Green Certificates advocate that this is a superior policy instrument compared to using fixed prices and privileged access to the market (as practised in Germany, see Jacobsson, 2002).
[7] In this, we may also include non-technology specific factors.
[8] A very useful study (Rickne, 2000) compares how universities in Sweden, Massachusetts and Ohio contributed to how these functions were performed in the case of biomaterials.
[9] Faulkner and Senker (1994) specify additional mechanisms.
[10] See Dasgupta and David (1994) for a discussion of this overall function of academic R&D.
[11] Universities can be seen as a reservoir of knowledge, which can be drawn upon at will, as was argued above.
[12] See also Dasgupta and David (1994) on this point.
[13] We would also expect that spin-offs are normally located close to their source (Lindholm-Dahlstrand, 1999)
[14] Professor Keith Pavitt kindly gave me access to this paper.
[15] Rickne (2000) notes that various types of ’bridging institutions’ are much less frequent in Massachusetts and judged to be less important by industry than in Ohio and Sweden but, even so, Massachusetts performs better in biomaterials.
[16] Henrekson and Rosenberg (2000) recognise that a somewhat different situation developed in terms of start-ups in the 1990s and attribute that, at least in part, to changing incentives.
[17] See Jacobsson et al. (2002) for a case study of how two new firms producing solar cells (Wurth Solar and Antec) were founded by exploiting the competence base of German R&D institutes.
[18] A further problem in comparing data on academic R&D across nations is that in some countries, e.g. US and Denmark, academic teachers have time for research built into their posts whereas in others, e.g. Sweden, lecturers have to find external funding for their research. In the former case, we would suspect that a lot of ‘hidden’ research is undertaken.
[19] In addition, as Pavitt (1998) emphasises, the output of the academic sector is a public but not a free good and smaller countries therefore have to pay a high entrance ticket to international networks in order to be able to draw upon the accumulated knowledge in the world. The potential of the academic sector to contribute with new knowledge (to the world) would therefore be less than what the share in GDP would tend to suggest for smaller countries.
[20] This exception is not complete though as biotechnology is an engineering field too.
[21] In other engineering fields, Sweden ranks higher. In material science, Sweden ranks as (no. 1); nuclear engineering, (no. 2); mechanical engineering, (no. 5); Chemical engineering, (no. 8).
[22] In the broader area that relies on capabilities in electronics and computer science, we find two additional classes: ‘Artifical Intelligence, Robotics & Auto Control’ as well as ‘Instrumentation/Measurement’. In the former field, Sweden ranks as no. 7 and in the latter as no. 2. ‘Instrumentation/Measurement’ is a knowledge field in which Sweden has had strength for some time (see Jacobsson, 1997) and the leading countries are not those which are ahead in other fields that rely on capabilities in electronics and computer science. Switzerland ranks highest, followed by Sweden, Finland, Netherlands, Israel and Germany.
[23] None of the methods appear to be satisfactory on their own; and some may be very misleading; in particular Meyer (2000) provides a potentially devastating critique of using citations to papers in patents as a means of establishing local ‘spill-overs, at least with a cross country comparative perspective.
[24] An example from the case of solar cells is an improved production process for crystalline silicon cells recently introduced by the German firm ASE.

[25] Computer Science and Telecommunications Board (1999) gives yet a further set of examples of the time scale involved.

[26] With respect to renewable energy technology, the strategic repositioning of ABB into such technologies came as a great surprise for many in 2000. For a case demonstrating the unpredictability in the evolution of a technological system, see Johnson and Jacobsson (2000).

[27] I have benefited here from discussions with Brian Loasby at the 2002 DRUID Winter Conference, Aalborg, Denmark, January 17-19th.

[28] This does not, however, mean that other benefits and mechanisms should be ignored – e.g. spin offs to realise some options should be stimulated in the sense that these mechanisms, as the others, should be free of obstacles.

[29] Other authors underscore this view, e.g. Hicks et al. (2000) and McMillan et al. (2000) for the US and Faulkner and Senker (1994) for the UK. For instance, Hicks et al. (2000) show that a US scientific paper among the top 1 per cent most highly cited papers is nine times more likely to be cited by a US patent than a randomly selected paper.

[30] See Goldfarb and Henrekson (2002) for a clear case of the latter.

[31] As Dasgupta and David (1994) point out there are more features of current Science Policy which may lead to an inability to manage this challenge.

[32] See Geuna (2001) for a discussion of the changing rationale for European university research funding and an exploration of negative unintended consequences. Goldfarb and Henrekson (2002) cite a case in biophysics and molecular biology where links to industry led to dissertations of little basic importance. We are aware though, that not all industry funding of academic R&D restricts academic freedom (Behrens and Gray, 2001 and Rickne 2000).

[33] We calculate with 2 470 PhD students, 507 Professors and 1 014 lecturers which were the number of fulltime equivalents in 1999 (SCB, 2001). We assume that lecturers should have 25 per cent of their time for research to support teaching and that professors should have 35 percent. We further assume that the students spend 20 percent of their time taking courses and that professors teach these courses. We assume that there are ten students per course and that each student takes 2 courses per year. Giving a PhD course is assumed to account for 10 per cent of a professor's yearly working hours. The salaries are assumed to be 18 000 SEK for PhD students, 36 000 for lecturers and 44 000 for professors. Social overheads are assumed to be 54 per cent and University overheads another 50 percent. The total estimate would come to 778 million SEK which was 71 per cent of the fixed funding for 1999 according to SCB (2001). The different cost items were as follows: professors' and lecturers' research to support teaching 214 and 250 million respectively, PhD students taking courses 246 million SEK and professors' teaching in these courses 68 million SEK.

[34] The study 'Forskning 2000' could be read as a 'desperate' attempt to address a perceived imbalance in the structure of funding.

[35] This example is based on Vinnova (2002).

[36] The same lesson can be drawn from the German wind energy programme (Johnson and Jacobsson, 2001).

[37] The close links between Swedish industry and the universities of technology are pointed to by Sörlin and Törnqvist (2000).

[38] Martin and Etzkowitz (2000) make a distinction between different 'species' of universities, acknowledging that land grant universities in the US and technical universities are closely linked to meeting societal needs.

[39] As Rosenberg and Nelson (1994, p. 347) conclude in an influential article: "… binding university research closer to industry, while respecting the condition that research be 'basic' in the sense of aiming for understanding rather than short-run practical payoff, can be to the enduring benefit of both".

[40] In this we strongly disagree with Sörlin and Törnqvist (2000) as well as with Goldfarb and Henrekson (2002) who argue that there may be a conflict between usefulness and scientific standards as indicated by publishing.

[41] In discussion with policy makers, I have made this point over the past decade illustrating with my own situation. Just imagine the opportunity of being able to influence the thinking of about 100 engineering students per annum by using your own research.

[42] In part, it was due to a decline in the number of graduated engineers and scientists in the US.

[43] It is not clear that all tiers follow market-based solutions.