A Strategy for the Analysis of Idea Innovation Networks and Institutions

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Abstract

The perspective of this paper is that variation in commercially successful radical product/process innovations among science-based industrial sectors can be explored by focusing on idea innovation networks. Idea innovation networks have six arenas reflecting research — basic research, applied research, product development research, production research, quality control research, and commercialization/marketing research. The paper develops two interrelated hypotheses. The first is that the greater the diversity of competencies or knowledges that are connected with frequent and intense communication within an arena and the greater the size of the arena, and the greater the likelihood that radical innovations will emerge. The second hypothesis involves the same kind of logic: if radical solutions are to occur in more than one arena, there must be intense and frequent communication among the different arenas involving radically new ways of thinking. Radical research solutions in one arena usually involve tacit knowledge and to be effectively communicated to another arena, both tacit knowledge and codified knowledge must be communicated across arenas. However, the communication of tacit knowledge is more likely to occur when there is frequent and intense communication across arenas.

In analyzing connectedness, the authors draw on the literatures about organizational innovation and organizational learning. In addition, they recognize that institutional environments shape the size of research arenas and the connectedness within and among them. The suggestion is that the more similarity there is across sectors, in patterns of research arena size and connectedness, the greater the support for a national system of innovation interpretation. Contrariwise, less similarity of network arena characteristics across sectors may mean more support for the strong role of globalization forces in affecting innovation.

Descriptors: business systems, globalization, institutions, national systems of innovation, radical innovation, social system of production

Introduction

There is increasing evidence that innovative capacity of a society is linked to its international competitiveness and its rate of economic growth, and for this reason the subject of innovation should be high on the social science research agenda (Dosi et al. 1988; Nelson 1993). This is particularly

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apparent for commercially successful radical product and radical process innovations: the former often represent the creation of whole new industries or market segments, and the latter represent considerable jumps in productivity. Internet services, biotechnologies, material sciences, and flexible manufacturing are examples of both types of innovation.

In addition to the organizational sociological literature on innovation (Damanpour 1991; Zammuto and O'Connor 1992; Hage 1999), a number of new literatures in both organizational and institutional analysis have emerged that are related to the process of radical innovations. These include literature on organizational learning/knowledge (Cohen and Sproull 1996; Conner and Prahalad 1996; Kim 1997, 1998; Van de Ven and Polley 1992), inter-organizational networks (Alter and Hage 1993; Dussauge and Garrette 1999; Doz and Hamel 1998; Gomes-Casseres 1996; Harbison and Pekar 1998; Inkpen and Dinur 1998; Mockler 1999; O'Doherty 1995), national systems of innovation (Archibugi and Pianta 1992; Edquist and Hommen 1999; Kogut et al. 1993; Nelson 1993) and modes of co-ordination (Hollingsworth and Boyer 1997).

This is a theoretical paper, and our objective is to suggest a strategy for understanding how research leads to commercially successful radical product and radical process innovations in research intensive industries. In doing so, we build on the little-cited paper by Kline and Rosenberg (1986) and develop the concept of 'idea innovation networks'. These networks exist at the level of an industrial sector and market sector, and each network has six different functional arenas in which various types of innovative processes occur. The six research arenas are basic research, applied research, research about product development, research on manufacturing processes, research on quality control, and research about the commercialization and marketing of products. We are not concerned with all social processes that occur within each of these six arenas, but only with research activities associated with radical product and radical process innovations. Each of these functional arenas has its own highly trained workers, dedicated research funds, and specific outputs. An idea innovation network is defined as the research activities in each of the six arenas and the connectedness within and among these arenas in a particular industrial sector. The implication within this definition is that the research activities in an arena may extend beyond the boundaries of a single firm or a single society.

If radically new, commercially successful, products are to emerge in an industrial sector, there must be linked research activity in each of the six arenas. Radically new knowledge need not occur in all six arenas, but the radically new knowledge (regardless of the arena) must be integrated with knowledge changes in other arenas if radically innovative products or processes are to occur — typically, these tend to occur in product development or manufacturing research. By analyzing both the arena of origin of the radical new knowledge and how research in other arenas is connected to the radical new knowledge, we can more precisely specify the process of innovation.

Why is there a need for a new strategy to study radical product and radical process innovation? First, there has been a change in the processes which Lawrence and Lorsch (1967) described for America firms, when most of the functional arenas were in a single firm, at least in research intensive industries in the United States. However, with the increasingly complex growth of knowledge, nowadays, it is usual to find various arenas located outside a single firm, especially those of basic and applied research. This change is reflected by the increase in the scholarly literature on joint ventures and inter-organizational networks, both within countries and at the global level, in a variety of industrial sectors (e.g. auto, aircraft, pharmaceutical, bio-technology). Perhaps the most striking evidence for this change is that some countries, without much basic research, have been able to exploit the findings of basic research in other countries and apply them to the development of new products. Still other countries have taken products developed elsewhere and become their dominant producers after conducting research on radically new manufacturing processes.

The drive behind all these processes is a trend towards organizations becoming more specialized. Because too diverse a set of competencies is difficult to integrate, firms are downsizing and spinning off distinctive units into separate firms. Furthermore, research organizations are finding that to perform well in a particular area, they must have a high degree of knowledge depth in a specific arena; that is, there must be a variety of sub-specialists and this, too, increases the propensity for specialization (Alter and Hage 1993). As these processes have occurred, many small high-tech organizations have emerged that focus on only part of the entire innovation process for a product, most notably in bio-technology, materials sciences, and information-based industries (Hagedoorn 1993; National Science Foundation 1996). Given these processes, a major theoretical problem is how the various functional arenas are connected to each other, as knowledge is more and more differentiated in separate organizations and in separate countries.

Second, more and more industrial sectors are becoming research-intensive, due to the increase in absolute terms of both public and private research expenditures (National Science Foundation 1998). In current dollars, the research expenditures in the United States in all kinds of chemicals went from 5 billion in 1980 to 22 billion in 1998, and the drugs sub-sector jumped from 2 to 12 billion. In the same time period, R & D expenditures in electrical products almost tripled from 9 to 26 billion; machines went from 6 to 15 billion, transportation from 14 to 29 billion, and instruments increased four-fold, from 3 to 13 billion.

In addition, the total expenditure for R & D has grown in most countries. Between 1981 and 1998, total expenditures on non-military research in constant US dollars (1992) increased by 66 percent in the United States and nearly doubled in Japan. In Germany, France, and Italy there was nearly a 50 percent increase during the same time period. Only the United Kingdom remained relatively stagnant (National Science Foundation 1998: Appendix 4). In the case of the United States, most of the increase reflected spending by business firms.

We suggest two concepts for describing and analyzing the idea innovation network in a particular industrial sector (Campbell et al. 1991; Guerrieri and Tylecote 1998; Kitschelt 1991: 460; Pavitt 1984). The first concept is the *shape* of the idea innovation network, as this reflects the amount of research activity in the various arenas, and can be measured by the number of researchers (technologists, scientists, and higher professionals) working on a problem, the level of research expenditures from various sources (both public and private), and the distinctive kinds and quantities of outputs, whether ideas, papers, patents, machines, or quality control instruments, etc. The second concept is the *connectedness* of the idea innovation network, which is defined by the amount of communication among actors within and across these six functional problem arenas. The form of communication can vary among actors within and across arenas, and the communicated outputs vary from arena to arena (e.g. scientific papers, patents, products). The more intense and frequent the communication, the more tacit the knowledge communicated among actors; and the lower the communication among actors, the more the communicated knowledge is simply codified in nature. The richer the communication among actors, the more both tacit and codified knowledge is communicated (Polanyi 1962, 1966; Lundvall 1992).

The task of understanding the degree of connectedness or communication among actors within and across arenas is critical for the study of the innovation process, especially since there has been a proliferation of joint ventures and inter-organizational *networks* as well as the development of many other kinds of linkages among firms and/or non-firms (Perrow 1984). An important distinction should be made between the connectedness within an arena — i.e. how much communication there is among actors working on similar problems — and connectedness among actors across arenas. A radical research solution within a particular arena requires a diversity of competencies or specialists who are strongly connected. Given the growth in the size of the research arenas, the new knowledge that is required for the development of a radical new product could be located in a variety of research organizations. The growth in the number of organizations makes the connectedness within arenas an important issue. Indeed, this is one reason why governments are encouraging research consortia; they help to facilitate the intense and frequent communication that allows for the quicker development of radical solutions (Aldrich and Sasaki 1995; Alter and Hage 1993; Browning et al. 1995. High connectedness within an arena can also be advanced by industrial parks and districts or propinquity (Debresson 1996; Lazerson 1993; Pyke and Sengenberger 1992).

However, once there is a radical solution *within* an arena, it must be communicated to other arenas as well, because the radical solution requires new kinds of research in each of the other arenas. This is most evident with radical product innovations. Typically, they require research on manufacturing, quality control and commercialization, and in order to create the radically new product, there may also have to be additional basic and applied research. However, radical solutions are not necessary in each of the six arenas. For the product to be commercially successful, what is necessary is that the radical solution in one arena is tightly connected to at least some of the other arenas. In this context, the 'probe and learn' strategy described by Lynn et al. (1996) is especially relevant.

Whenever there are radical product innovations in research-intensive industries, there is usually a high degree of connectedness among the arenas of product development, marketing, quality control, and manufacturing. What is variable, is the degree to which tight connectedness is necessary between basic and applied research arenas, on the one hand, and, on the other, the remaining four arenas. An important theoretical question is why there is this variability.

The explanation is the *speed* with which a radically new product/process is tied to radical advance in basic science. When those who develop radically new basic science have a monopoly on the knowledge, only they can develop new products based on that knowledge. On the other hand, if there is no monopoly on the basic and applied science, the knowledge tends to diffuse and become codified, and it is not necessary for tight connectedness to exist between the basic and applied science arenas and the other four arenas. However, the lack of tight connectedness will result in slower speeds of diffusion.

Thus, when the atomic bomb was developed, the basic science arena and the product development arena were tightly linked, because the same people did both types of work. In certain bio-medical areas, those doing the basic research are tightly linked with research in product development because there should be little time lag between the new basic knowledge and the new product. The basic scientists have a monopoly on the knowledge and only they can develop a new product. Hence, the arenas of basic and applied science, and product development must be tightly linked. When most radical new products in research-intensive industries are developed, there may be a need for some additional basic and/or applied science, but only of an incremental nature. In these cases, there is no need for tight connectedness between the basic science and the product development arena; the same people need not be doing both the basic and applied research, and the product development research. This was the situation with the Walkman, anti-lock brakes, or high-speed trains.

The test of any proposed new research strategy is the kind of theoretical problems it can highlight. Among other advantages, our concepts about the shape and connectedness of the idea innovation network help to explain why some countries have more radical innovations in some sectors or market segments than others. Thus, our first advantage is the ability to explain differences across countries and even the market segments within them. An understanding of these processes should assist governments to understand in what arenas they should invest in order to stimulate commercially successful radical products and radical processes.

Second, the idea innovation network, by drawing on a number of literatures, including those on organizational learning, inter-organizational networks, modes of co-ordination, and national systems of innovation, helps to build a bridge between the meso-organizational level of analysis and the macro-societal or institutional level, and thus helps to facilitate an eventual synthesis of the literature involving these two levels of analysis.

Third, by identifying the six functional problem arenas that are linked with each other, one can study the process of innovation as a nonlinear one that can start in any single arena and move back and forth, depending upon the kinds of connectedness within and among the arenas. Our perspective shifts the focus from the over-emphasized arena of basic science to some of the other arenas, and especially to research solutions about manufacturing, quality control, and the commercialization of products.

Finally, another advantage of our concept of idea innovation network is that it suggests *what* kinds of knowledge each arena produces and in *which* kinds of organizations or networks the acquisition (i.e. learning) and production of knowledge takes place for radical product/process innovations to occur. Furthermore, it implies the need to have some form of co-ordination within and across the different arenas, so that learning can take place, and by focusing on the strength of connectedness, it suggests *how much* knowledge is being transferred among different arenas. All of these issues are matters of concern in the study of the process of radical product and process innovations.

The Problematic and the Relevant Literature

The Problematic

In addressing the processes creating radical product innovations, we define these as products which (1) improve performance significantly (e.g. high speed trains, anti-lock brakes, HDTV or digital television), (2) were previously unavailable (e.g. VCRs, fax machines, scanners, wireless telephones, Viagra, anti-depression drugs), or (3) represent the subtraction of some undesired quality (e.g. reduction of manufacturing pollution with scrubbers or from cars with catalytic converters, the elimination of sugar and fats in foods). We define radical process innovations as significant improvements in the throughput (e.g. automatic cargo loading and shipping [Walton 1987], the new process of making plate glass, coaxial cables, robots, and flexible manufacturing [Zammuto and O'Connor 1992]). One can imagine other kinds of radical product/process innovations (Henderson and Cox 1990), but these cover the major kinds. Whether in radical products or radical processes, the basic theme is one of discontinuity (Anderson and Tushman 1990).

To understand the organizational and institutional environments from which radical process and radical product innovations emerge, we build upon the ideas of Kline and Rosenberg (1986) to develop the concept idea innovation network. Our definition of an idea innovation network emphasizes the development of new knowledge from research in each of the arenas, and the connectedness within the arenas that develops radical solutions as well as the connectedness across the six arenas. As we review the relevant meso and macro literatures, we observe that our perspective offers a number of new insights about learning by actors within and across arenas. At the meso level, the most important topics are organizational learning/knowledge and inter-organizational relationships involving learning across organizations. At the macro level of analysis, the most important topics are either regional (Debresson 1996) or national systems of innovation and modes of co-ordination.

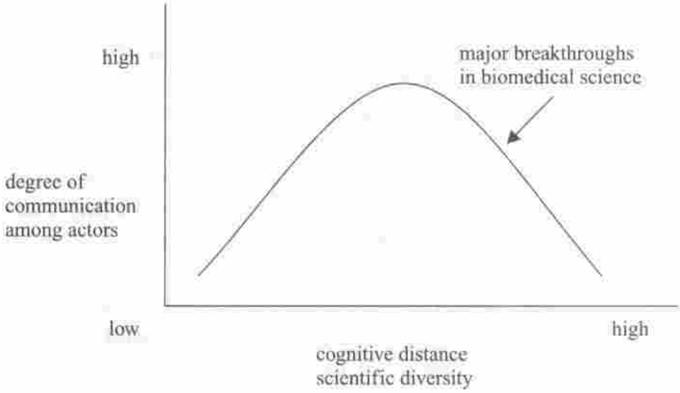
For radical process or radical products to occur in any industrial sector, a number of problems must be addressed. For this purpose, the innovation process described by Kline and Rosenberg (1986) is most helpful. Their model carries the logical implication that, in commercially successful radical innovations, the research solutions in one arena are influenced by the ideas and opportunities in other arenas. Obviously, a product that does not have desired attributes and a certain level of customer-preferred quality is unlikely to do well, although, frequently, products are developed without much research concerning the needs of customers.

Although the Kline and Rosenberg's (1986) model of the innovation process emphasized incremental innovations, our position is that most arenas are likely to be involved with radical product and radical processes innovations that are commercially successful. The reasons for this are straightforward: incremental product improvements can be accomplished within a firm that is already producing a product, probably with only minimal product research. In contrast, radical product and radical process innovations necessitate research in arenas other than product development. For example, the development of high-speed trains required the redesign of every aspect of railroad transportation, including the process of ticketing. Radical new products in chemistry or in the pharmaceutical industry require not only basic research, but also pilot plants to do research on manufacturing and quality control.

Another departure from Kline and Rosenberg (1986) involves (1) connectedness within arenas where radical innovations emerge, and (2) connectedness across arenas when radical solutions are necessary. Our arguments involve two interrelated hypotheses. The first is that the greater the diversity of competencies or knowledges *that are connected with frequent and intense communication* within an arena and the greater the size of the arena, the greater the likelihood that radical solutions will emerge. There is a long research tradition on organizational innovation that supports this hypothesis (Hage 1965, 1999). More recently, a large-scale comparative research project on major breakthroughs in the bio-medical area demonstrates the importance of frequent and intense communication among actors from diverse backgrounds if major breakthroughs are to occur (Hollingsworth and Hollingsworth 2000 forthcoming; Hollingsworth et al. forthcoming).

Our second hypothesis involves the same kind of logic. It states that if radical solutions are to occur in more than one arena, there must be intense

Figure 1
The Impact of Degree of Communication and Cognitive Distance on Making Major Breakthroughs in Biomedical Science



Note: We are indebted to Bart Nooteboom for the insights in this figure.

and frequent communication among the different arenas, involving radically new ways of thinking. Radical research solutions in one arena usually involve tacit knowledge, and to be effectively communicated to another arena, both tacit knowledge and codified knowledge must be communicated across arenas. The communication of tacit knowledge is more likely to occur, however, when there is frequent and intense communication across arenas (Inkpen and Dinur 1998; Nonaka and Takeuchi 1995; Polanyi 1962, 1966; Lundvall 1992).

Buried in this discussion is a basic dilemma, as illustrated in Figure 1. Increasing the diversity among actors engaged in research increases the amount of novelty involved in a radical solution, but the increased diversity makes communication and connectedness among actors more difficult. The diversity is facilitated by the growth of a variety of research organizations, both within and across arenas, as part of the specialization process that has already been described. However, this same process reduces the frequency and intensity of communication among organizations, especially when they are located in different regions and even nations.

Commercially successful radical product/process innovations do not require radical research outcomes in all six research arenas. Ideas developed in one arena may necessitate radical research solutions in one or more arenas, but not in all. Indeed, this is one of the attractive features of our framework. It recognizes that ideas or research solutions within as well as across arenas only need to be weakly connected, if no more than an incremental solution is required (Hansen 1999).

Furthermore, our perspective points out that radical innovations in research-intensive industries do not necessarily require heavy investments in basic science — a bias of the literature (Stokes 1997) — but, instead, may occur in applied research or product development or in manufacturing. Nor is radical innovation always a linear process from basic science to product development, as both Kline and Rosenberg (1986) and Stokes (1997) have reminded us. For example, the decision at DuPont to make nylon began in the product development arena and from there the firm turned to the basic science research arena and conducted research on polymer chemistry. In contrast, the major breakthroughs in bio-medical research have frequently led bio-medical scientists to establish biotech companies, which then attempt to develop new gene therapies. Other radical products may not require anything but incremental research in basic science. These examples suggest whether or not the process is linear, and that the degree of the importance of basic science varies by the nature of the market segment. In fact, we are impressed by the large number of cases in which a firm first works on the development of a new product in the product development arena and then begins to search for needed information in basic science and then finds that it needs only incremental advances in the science.

Why six arenas and why these particular six? Readers familiar with Lawrence and Lorsch's (1967) work will recognize that these six arenas have been in the literature for some time. Indeed, in their work, they stressed the need to have separate functional departments for basic research, applied research, product development, and manufacturing because different skills, expertise and ways of thinking were involved. What is different in our approach is the suggestion that, increasingly, these are not just functional departments, but arenas that exist across firms, and even non-firms, and that some relevant research is likely to take place outside the firm and even outside the country. This is especially true for radical product/process innovations. Although basic research may occur in one country, firms in other countries may readily 'pick-up' on these ideas (Stokes 1997). Japan's exploitation of the American patents on robots is a good example (Porter 1990), and below, we discuss examples involving South Korea and Taiwan. Furthermore, some countries may not have a strong tradition in basic research arenas, but if they successfully monitor developments elsewhere, they might develop their own radical product/process innovations (Møller 1991; Petrella 1995; Unger 1999). The reverse is equally important. Countries may have a lot of basic research and strength in applied research and product development, but may not develop commercially successful radical product/process innovations because they lack enough communication across the relevant arenas, whether these are within one firm or across firms (Lynn et al. 1990; Zammato and O'Connor 1992). Admittedly, it is sometimes difficult to distinguish among basic research, applied research, and research on product development (see Table 1).

Some additional discussion is necessary about two arenas: the arenas involving research on quality control and on the commercialization of products. In some market segments, research on quality control is crucial. In biotechnology industries, for example, advances in product quality influence market share. Clinical trials in pharmaceuticals are one of the most expensive parts of the entire innovation process. And with semiconductors, a great deal of research is concentrated on how to achieve quality control in the manufacturing process.

It may strike some readers as a bit strange to focus on research on com-

Table 1
Functional Arenas in the Idea Innovation Network

Functional Arena	Definition
Basic research	Experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.
Applied research	Original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.
Product development or product innovation	Systematic work, drawing on existing knowledge gained from research and practical experience, that is directed to producing new materials, products and devices, including prototypes.
Production research or process innovation	Research to design new manufacturing products or processes.
Quality control research	Research aimed to improve the quality of products as well as research in order better to understand and control the effects of products.
Commercialization research	Research designed to understand the needs of customers or to improve the distribution channels.

mercialization of products, but as Lynn et al. (1996) observe, many companies that have successfully produced radical innovations have tended to create multiple variations of their ultimate products for different markets, and from this practice of 'probe and learn', they finally produced their revolutionary product: examples include General Electric in the development of computerized axial tomography, Corning Glass and optical fibers, Motorola and the wireless phone, and Searle with NutraSweet. Oracle maintains a very large set of relationships with firms in different countries that carry out prototype testing to meet the customer needs in particular countries. Likewise, Microsoft and other companies do research on how best to market products in different countries (Mockler 1999).

The Relevant Meso Literatures

Although there is a relatively large literature concerned with the impact of organizations on innovations (Damanpour 1991; Zammuto and O'Connor 1992; Hage 1999), most of this research has focused only on the internal organizational characteristics that affect the rates of innovation and has ignored the external aspects of the innovation process. Moreover, the literature has not placed much emphasis on radical innovations, an exception being the scholarship on radical process technologies (Zammuto and O'Connor 1992). In contrast, Lundvall (1993) and others (Häkansson 1990; Van de Ven and Polley 1992) have argued that innovation and interfirm cooperation can be explained by interactive learning. The ideas of Kline and Rosenberg (1986) are suggestive, because there is the implication in their work that there are distinctive arenas and that the knowledge one arena produces is acquired/learned by other arenas. We extend this thinking to suggest that actors maximize the conditions for radical innovations when there is acquisition of knowledge (i.e. connectedness) across arenas of basic research, applied research, research on product development, research on manufacturing, research on quality control, and research on commercialization of products.

There has been a large and growing literature on organizational learning (Cohen and Sproull 1996; Conner and Prahalad 1996; Kogut and Zander 1996), the production of new knowledge (Brown and Duguid 1998; Grant 1996; Nonaka and Konno 1998; Nonaka and Takeuchi 1995) and/or the absorptive capacity of organizations (Cohen and Levinthal 1990). These ideas have emerged from the resource-based view of the firm, in which knowledge is increasingly seen as the critical resource (Conner and Prahalad 1996; Foss 1996). This perspective has lacked a theory of the kind of knowledge that is acquired (i.e. learning) by arenas, and generally, this literature has emphasized the internal mobilization of tacit knowledge, rather than external linkages for learning. The major exception is the literature on the absorptive capacity of an organization (Cohen and Levinthal 1990), which emphasizes research as a mechanism for absorbing knowledge from outside the organization.

Much of the inter-organizational network literature has a dynamic quality to it and has stressed the considerable changes in the kinds of networks or strategic alliances and joint ventures that are needed, as ideas move from the market place to joint research and product development (Hage and Alter 1997; Hagedoorn 1993; Harbison and Pekar 1998). In this literature, there is the argument that strategic alliances are made for learning purposes, especially in what are called research-intensive industries such as information technology, biotechnology and new materials (Mockler 1999; Hagedoorn 1993; Petrella 1995). What this literature has not done is to indicate all the different kinds of knowledge that must be produced if radical innovations are to occur. Instead, it has simply tended to emphasize the need for a joint venture or strategic alliance among firms (see special issue of *Organizational Science* 9/3 1998). Some sense of the range of knowledge needed for radical innovations is found in the few studies that relate the nature of the inter-organizational linkages in the innovative process (Abramson et al. 1997; Browning et al. 1995; Oerlemans et al. 1998; Powell and Brantley 1992). However, these studies have not defined each of the distinct problem areas that have to be addressed in the process of radical innovation, whereas our emphasis on the six functional arenas suggests six different problem areas which must be interlinked if an industrial sector is to have radical/process innovations.

The Relevant Macro Literatures

Once one recognizes that there are six functional problems to be confronted in radical product/process innovations, problems about the size of each of the six arenas and the extent of connectedness among actors within and among arenas become important theoretical issues. An understanding of these issues is facilitated by focusing on a society's macro-institutional arrangements. Societies vary in how much research necessary for innovations takes place in universities and technology centres and other kinds of non-firm organizations. They also vary in the amount of communication that occurs among and between these organizations and the firms that ultimately produce the radical product/process innovations. Two macro literatures are especially helpful in understanding the relative sizes of the research arenas and their degrees of connectedness: (1) the literature on national systems of innovation and business systems (Archibugi and Pianta 1992; Edquist and Hommen 1999; Kogut et al. 1993; Hollingsworth 1997; Nelson 1993; Whitley 1992a, 1992b); and (2) the literature on various modes of co-ordination (Campbell et al. 1991; Hollingsworth and Boyer 1997; Williamson 1985) especially inter-organizational networks (Alter and Hage 1993; Dussauge and Garrette 1999; Doz and Hamel 1998; Gomes-Casseres 1996; Harbison and Pekar 1998; Inkpen and Dinur 1998; Mockler 1999; O'Doherty 1995).

Nelson (1993) and others have suggested that countries vary in the sectors in which they are innovative, and it is the effort to explain this variation that led to the concept of national systems of innovation. To explain differences, scholars have typically focused on a society's science, education, and financial systems. One strength of this literature is that it has called attention to the relative size of the basic research, applied research and product development arenas. However, this literature has given very little attention to research in the arenas of manufacturing, quality control, and the commercialization of products. Another limitation of this literature is that it has not focused on transnational forms of connectedness. Yet the transnational connectedness among organizations helps to explain why they are able to make radical innovations, even if the countries in which they are headquartered are weak in research arenas. Such firms are connected with organizations in other societies which are strong in such arenas (Møller 1991; Petrella 1995; Unger 1999).

The comparative business systems (Archibugi and Pianta 1992; Edquist and Hommen 1999; Kogut et al. 1993; Whitley 1992a, 1992b) and the social systems of production literature (Hollingsworth 1997) have argued that a society's educational, research, financial, business, and political systems influence its international success in particular market segments. However, this literature has not generally concentrated on innovation as such, let alone radical product/process innovations, but has been concerned with describing the overall configuration of institutional arrangements that affects the way in which firms are structured, but not with how research arenas are separated or combined in different societies. Nor does the literature explain why firms, which previously had not performed well in a particular industry, can leapfrog their competitors in other countries and become world leaders in a particular industry.

One literature which is relevant to these problems and which confronts the issue of how arenas are connected both transorganizationally and transnationally is that involving non-market modes of co-ordination (Campbell et al. 1991; Hollingsworth and Boyer 1997; Williamson 1985). The market tends *not* to be very effective in the communication of tacit knowledge, which is likely to be critical in radical product/process innovations (Inkpen and Dinur 1998). In the cross-national literature, one finds a focus on a number of non-market modes of co-ordination which facilitate communication within and among arenas. *Indeed, we suggest that despite the emphasis of the scholarly literature on the importance of markets, our theoretical perspective calls attention to the need for a variety of co-ordination mechanisms to connect both firms and non-firms within and across arenas.*

We have already mentioned the literature on inter-organizational networks as a critical mode of co-ordination both within (Aldrich and Sasaki 1995; Browning et al. 1995) and among arenas (Dussauge and Garrette 1999; Gomes-Casseres 1996; Inkpen and Dinur 1998; Kogurt et al. 1993; Mockler 1999; Valentin 1995). In addition, we briefly mention two other non-market modes of co-ordination that are important in stimulating radical innovation: (1) the state, and (2) associations of various kinds. The most obvious influence of the state is through scientific research policies and laws about property rights (Hollingsworth and Boyer 1997), but the state, through its industrial policies, may facilitate radical product/process innovations within particular market segments (Cohen 1992; Casper 1999), or by the creation of industrial parks (Monck et al. 1988). Associations can encourage members in various ways to work together to create their own research centres (Pyke and Sengenberg 1992; Schneiberg and Hollingsworth 1990), which, in turn, can create a climate conducive to the adoption of radical process technologies (Abramson et al. 1997: 156; Piore and Sabel 1984; Walton 1987).

Our concepts, the shape of the research arenas and their connectedness, resonate with several understated themes in these literatures. The national systems of innovation literature emphasize the non-firm location of much basic and applied research, but have tended to minimize transnational locations, and while the non-market modes of co-ordination literature have focused on the ways in which arenas can be connected, they have not placed much emphasis on the firm/non-firm connections that are vital in radical product/process innovations, nor has the literature on modes of co-ordination been associated with the strength of connectedness.

The Shape of Idea Innovation Networks and the Strength of Connectedness Within and Among Arenas

An idea innovation network is a configuration of six distinct functional arenas, each of which produces ideas which circulate to other arenas. Each of these six research arenas performs different *research* activities, but all are central to the innovation process. To compare industrial sectors across countries and to compare across sectors in the same country, we have selected *two* properties: (1) the *shape* of the six research arenas, and (2) the *strength* of the connectedness within and among these arenas.

The Shape of Idea Innovation Networks

Why in measuring the shape of the idea innovation network have we emphasized the number of researchers, the extent of research expenditures, and the amount of knowledge output in each arena? Our reasons are both theoretical and methodological. The economics literature has demonstrated that the number of researchers combined with expenditures predict the level of innovative output (Wood 1998; Debresson 1996; Kleinknecht and Bain 1993; Leontief 1993). In addition, the number of highly trained researchers and the level of expenditures for research are indicators of an arena's capacity to absorb new knowledge (Cohen and Levinthal 1990). These three variables also emerge again and again in the innovation literature (Guerrieri and Tylecote 1998; National Science Foundation 1996).

Many aspects of these measures are available in a variety of data sources. For example, the OECD publishes expenditure data on basic research, applied research, and product development. The European Union (*The Community Innovation Survey* European Commission 1997) has developed a more refined measure of expenditures on research in the arenas of manufacturing and marketing, although not on quality control. There are numerous measures of codified knowledge (Kleinknecht 1993, 1996; National Science Foundation 1996). For basic and applied research, for example, there is voluminous data on papers classified by scientific discipline as well as by citation indices — an indicator of the quality of the papers (Guerrieri and Tylecote 1998; National Science Foundation 1996). Despite some of their limitations, patent data as a measure of codified knowledge can be quite illuminating for the study of certain sectors, and good data on patents by both sector and country is now available (Archibugi and Pianta 1992; Pavitt 1984; Soskice 1996). Moreover, the number of citations in patents of other patents is a measure of the quality of the patent (National Science Foundation 1996).

Overall, the output of research on product development can be measured by the number of radical products, or by the development of radical processes such as that of new manufacturing technologies. For example, European data are available in *The Community Innovation Survey* (European Commission 1997). Moreover, this survey includes extensive firm-level data about the degree of radicalness of new products and process technologies.

The Strength of Connectedness

One of our main concerns is with the strength of the connectedness (i.e. communication) among actors, whether within or across arenas. Connectedness is measured by the intensity and frequency of the interaction of individual researchers, work groups or organizations within and across arenas. With intense and frequent interaction among actors, there is high potential for communicating both tacit and codified knowledge, and, when combined with diversity, there is an increased likelihood of radical research solutions. Thus, connectedness addresses the communication of tacit and codified knowledge, both within and across arenas in an idea innovation network (Lundvall 1992; Meeus et al. 1999; Valentin 1995).

For example, to take a single industry (the pharmaceutical industry), we note that researchers in the product development arena may be located in universities, free standing research institutes, pharmaceutical firms, and/or other types of organizations. Increasingly, there must be communication among organizations in this arena if radical innovation is to occur. In short, diverse actors need to be connected. However, if there are to be radical and commercially successful new products, researchers in product development must also be in frequent communication with researchers in other arenas. To have a successful product, it is necessary to have a high level of connectedness among researchers in basic science, in the manufacturing process, in quality control, and in product development. Because each of these types of research skill is separate, we increasingly find that firms handle the connectedness between product development and/or applied research and basic research via joint ventures or joint publications with researchers in universities and other research centres. Other joint ventures connect a variety of firms with pharmaceutical companies that specialize in solving the problems associated with manufacturing, quality control, and the commercialization of products (Malerba and Orsenigo 1993: 54–57).

There are barriers to connectedness that should also be discussed. Researchers in each arena face separate challenges, as each arena addresses different fundamental problems and thus represents a distinct way of thinking (Lawrence and Lorsch 1967). Again, we have the theme of connecting diversity. As a result of these differences, relevant ideas in basic science, in new manufacturing techniques, or in quality control are often not communicated across arenas as rapidly as they might be. The problem of communication within and across arenas is compounded as the arenas grow in size, because the number of research organizations and firms within each arena proliferate. As the size of arenas increases, the sheer number of potentially interesting ideas often becomes overwhelming, further exacerbating the problem of communication of information within and across arenas. Moreover, secrecy within research organizations inhibits the free flow of knowledge within and across arenas.

Given the speed with which actors can communicate with each other around the globe, a problem results from the sheer volume of ideas in papers, patents, reports, telephone conversations, and e-mails, so much so that a great deal of information necessary for effective communication among actors within and across arenas is lost. A considerable amount of tacit knowledge is necessary before much codified knowledge can be comprehended and transferred. In short, effective communication of information requires frequent and intense face-to-face communication. Thus, the highest degree of connectedness occurs when both tacit and codified knowledge are communicated, and this requires intense and frequent communication among actors (Polanyi 1962, 1966).

The methods used to assess the strength of connectedness in one arena in one organization can also be employed to measure the strength of connectedness across organizations. Some of the common measures for measuring the strength of connectedness both within and across arenas and across organizations are as follows: (1) the transfer of people from one research group to another, both within and among organizations; (2) joint research projects involving face-to-face collaboration among researchers, as distinct from long-distance collaboration; (3) joint publications; (4) the strength of managerial, financial, and research ties among organizations in joint ventures; and (5) the strength of ties among actors in research consortia (Nieminen and Kaukonen 1999). There are numerous sets of data from which one may obtain measures of the connectedness/communication among actors within and across arenas. For example, the European Commission's (1997) *Community Information Survey* also has very useful data about communication among actors across arenas in organizations. Comparable data are published by the US government (National Science Foundation 1996; Unger 1999).

Already, there are a number of studies which are relevant to the connectedness of actors within and across arenas. The literature on industrial organizations is one such example (Chandler 1977), and the industrial districts literature is another. Moreover, the role of trade associations engaged in research of various kinds for their members constitutes another example (Schneiberg and Hollingsworth 1990). Also, as we have seen, there is a growing literature on joint ventures (Inkpen and Dinur 1998; Powell 1998; Van de Ven and Polley 1992) and inter-organizational relationships (Doz and Hamel 1998; Gomes-Casseres 1996; Häkansson 1990; Lundvall 1993) that addresses the issue of connectedness. What these literatures have failed to examine, however, is how much diversity among actors is involved, and how strongly connected they are, and the consequences of these processes for radical product innovations.

We want to maintain a clear distinction between connectedness within arenas and connectedness across them. This is complicated by the fact that arenas can be within the same firm or in many different organizations. Moreover, arenas and/or organizations may be in the same or different countries. Theoretically, one can distinguish four kinds of settings (firm or non-firm) in which connectedness occurs: (1) single arena in a single organization; (2) multiple arenas in a single organization; (3) single arena in multiple organizations; and (4) multiple arenas in multiple organizations. Each of these four possible settings is briefly discussed with a particular focus on ways in which strong connectedness combined with diversity might be achieved.

Single Arena in a Single Organization

Large research organizations, whether universities or technology centres or firms with their own R & D, can have multiple research teams and centres involved in the same general market segment or industrial sector. Our own research demonstrates that the American universities tend to have a number of structural barriers to the diffusion of knowledge across differentiated units within the organization (Hollingsworth and Hollingsworth 2000). In these instances, one can say that there is low connectedness within the basic research arena located in a single organization.

The opposite can also be the case. Bio-medical research organizations such as the Rockefeller Institute, the Pasteur Institute, and the Laboratory of Molecular Biology historically had a number of major breakthroughs in bio-medical research, primarily because they had intense and frequent interaction among many scientists (i.e. tight connectedness) (Hollingsworth and Hollingsworth forthcoming; Hollingsworth et al. forthcoming).

Firms such as General Motors, Toyota, IBM, Imperial Chemical, General Electric, DuPont, have multiple plants producing the same products, as well as multiple product development centres and multiple marketing units, etc. Thus, if a research arena is located in many sites, research from one site may not be diffused to other sites (Womack et al. 1991).

There is high communication/connectedness when there is frequent and intense communication among the various actors within an arena of an organization. The more frequent and intense the communication among actors, the more tacit knowledge is communicated among them. Less frequent and intense communication, however, means that it is primarily codified knowledge that is communicated (Hollingsworth and Hollingsworth 2000; Hollingsworth et al. forthcoming). In this case, the incidence of radical breakthroughs within an arena is likely to be reduced.

Multiple Arenas in a Single Organization

Much has been said about this problem since the work of Lawrence and Lorsch (1967), who discussed the various mechanisms for creating tight connectedness among basic research, applied research, product development, manufacturing, quality control, and the like. More recent discussions of these ideas and, in particular, the smooth transfer of tacit and codified knowledge across arenas within firms are found in literature on some large Japanese organizations, where researchers in product development, quality control, and marketing are very tightly linked together (Nonaka and Konno 1998; Nonaka and Takeuchi 1995). Applied researchers move into production and marketing, while those in marketing and/or production often move into basic and applied research. This type of tight coupling or interactive learning within firms facilitates product development and process innovations and can be particularly effective for codifying tacit knowledge (Aoki 1988; Grant 1996; Malerba and Orsenigo 1993; Hollingsworth 1991; Kodama 1995; Nonaka and Takeuchi 1995).

The absence of tight connectedness across arenas helps to explain why a number of major American firms, which had quite extensive basic research, developed radical products, but were unable to commercialize them or even to put them into production. The list includes IBM, Xerox, RCA, GM and

GE. One of the most striking instances in the United States was success with early research on the development of robots, but failure to commercialize them successfully (Porter 1990). The Japanese were able to develop robots more successfully because their firms had tight connectedness across multiple arenas. The key point here is that without well-connected research in manufacturing, quality control, and commercialization, the potential of a new product is not likely to be realized. American companies such as Corning Glass and Motorola, that had successfully commercialized radical product innovations, had tight connectedness across a variety of arenas (Lynn et al. 1996; Porter 1990).

Single Arena in Multiple Organizations

Even in middle-sized or small countries, there is likely to be more than one research organization or firm involved in any particular arena. With publications and patents, there is generally a quick movement of codified knowledge from one organization to the next, but this is not necessarily the case with the transfer of tacit knowledge which requires intense and frequent interaction among actors. It is in this context that the discussion of research consortia becomes especially interesting. It reflects an attempt to connect the diversity within an arena, most typically either basic research and/or applied research (Aldrich and Sasaki 1995; Browning et al. 1995).

Multiple Arenas in Multiple Organizations

It is when we move to this fourth category, across arenas and organizations, that the full complexity of the problem of connectedness is revealed. A good example of this complexity is the biotech segment of the medical industry. In the United States, there are a number of joint ventures, joint research projects, and joint publications among universities, various research institutes and biotech firms that are connected in varying degrees with the arenas of applied research and product development. Scientists in American research universities are allowed to be staff members of these biotech companies and owners as well. Moreover, many of these organizations have various kinds of linkages with pharmaceutical firms in the manufacturing arena. This is a market segment in which a number of these joint ventures are global in scope. Not only do American pharmaceutical companies have multiple research centres in the United States and Europe, but they also have multiple joint ventures with biotech firms. The same is true for German, British and Swiss pharmaceutical companies. In all of these countries, in these market segments, there is a great deal of connectedness among actors across organizations, arenas, and countries (Casper 1999; Malerba and Orsenigo 1993, 1997; Powell 1998).

Many American biotech firms are in close proximity either to the National Institutes of Health or to American research universities. In turn, a number of the bio-tech firms are closely linked to each other and to pharmaceutical companies, which have tightly connected manufacturing research, quality control research, and research on commercialization. Various studies call attention to how tightly connected the bio-tech firms and pharmaceutical companies are to each other, in which kinds of arenas tight connections exist, and what kinds of relationships among specific arenas lead to better learning and more radical product innovations (Powell and Brantley 1992; Powell 1998; National Science Foundation 1996; Malerba and Orsenigo 1993). In contrast, the absence of tight coupling among German universities and biotech companies in that country has had a strong negative effect on the development of radical products (Casper 1999).

Obviously, focusing on joint ventures will not necessarily tell us how much communication is actually occurring among actors. Ideally, one wants to measure the tightness of the coupling among actors. Nor are joint ventures the only ways in which organizations in different arenas can collaborate. For example, in the agricultural sector, there are a variety of ways in which connections are made among agri-bio-tech firms, universities, and agricultural firms (Malerba and Orsenigo 1993, 1997; Powell 1998).

Some of the more interesting examples of connectedness across arenas and across firms are those that involve multiple firms as well as multiple arenas. Airbus stands out as a shining example, but it is not the only one. There are the various inter-organizational strategic alliances — both national and global — designed to develop radically new products, involving interactive TV, video CDs, global telecommunications, and RISC chips (Gomes-Casseres 1996; Malerba and Orsenigo 1993, 1997). However, the literature on these arrangements has not systematically examined the connectedness within arenas across firms and, *vice versa,* within a global context. Logically, this would appear to be the next step in order to gain an understanding of why strategic alliances vary in their capacity to develop radical product innovations.

Another way to pursue ideas about the importance of the size of arenas and the degree of connectedness within idea innovation networks is to examine sectors or market segments in which countries were behind in an industry and then made such significant advances that they became either technological leaders or at least capable of producing radical product/process innovations independently. Here the problem is whether a country that was a laggard in an industrial sector could create arenas and then connect them well enough so that they were not only capable of making radical/process innovations, but even became world-class leaders. Two interesting examples of this are the development of the Taiwanese and Korean semiconductor industries. Both are virtually textbook examples of the construction of the six arenas, that became tightly connected via a variety of mechanisms.

The Taiwanese government created a set of inter-organizational networks centred in an industrial park, Hsinchu, that included: (1) several technological universities, (2) the Technology Research Institute (ITRI) which included the Computer Communications Laboratory, (3) private-sector firms, both large and small, (4) government funding agencies, and (4) inter-organizational structures, e.g. trade associations and product development consortia, that helped coordinate various aspects of the network.

The state allocated substantial funding across time to increase the size of the arenas, and in addition, provided a variety of economic incentives for firms to locate in the industrial park (Matthews 1997: 29–30).

ITRI became a penultimate learning organization that monitored what was occurring throughout the world in its designated areas, of which semi-conductors was only one. It transferred its acquired knowledge to private firms, both large and small. However, it was only one co-ordination mechanism. Trade associations also facilitated the diffusion of knowledge across arenas, and finally, the private organizations also engaged in learning via licensing, joint ventures, and purchases of small high-tech companies in the United States.

In South Korea, there was a similar example of a sectoral laggard which leapfrogged to become a world leader. There it was a single company — Samsung — which was able to rival Toshiba and Intel, because it was the first company to produce a 256M DRAM chip (Kim 1997). Again, the story is one of organizational learning, but in this instance, accomplished through the connectedness of arenas within a single company.

As part of the learning process, Samsung sent their engineers to American firms to learn the industry. It organized two idea innovation network teams that included all six arenas, one of them located in Silicon Valley and the other in Korea. However, the two teams were tightly connected with each other, and it was the tight connectedness of the arenas in the two networks which facilitated the acquired knowledge to result in radical innovations (Kim 1997: 88–89).

In summary, Taiwan and Korea illustrate two quite different pathways for a country to become a world leader in a particular technology. In both cases, there was the creation of an idea innovation network, in which the arenas substantially increased in size and where they were connected with other organizations in other countries via a variety of mechanisms. Taiwan did this by creating an industrial district that housed an inter-organizational idea innovation network, while Samsung created an idea innovation network within a firm.

Many of these same ideas can also be applied to the problem of radical process innovations, though Zammuto and O'Connor's (1992) review of the differential success with advanced manufacturing technologies indicates that there are some striking differences among countries in their ability to develop and implement radical process technologies. In a careful study based on a number of sectors in the United States, Jaikumar (1986) found that basic, applied and product development research were not connected well to research on improving manufacturing processes. In contrast, the arenas in a number of Japanese firms in numerous industries *are* tightly connected, and there is literature which suggests that it is this difference in the connectedness across arenas, but within firms, which helps to explain why a number of American firms failed to achieve the discontinuous leaps in process innovation while the Japanese firm succeeded (Aoki 1988; Nonaka and Konno 1998; Nonaka and Takeuchi 1995).

Discussion

Above, we have made several suggestions as to how our perspective provides new insights concerning the conditions under which radical product and radical process innovations occur. By confronting the four literatures on organizational learning, inter-organizational relationships, modes of co-ordination and national systems of innovation, we can address the following issues: (1) How can modes of co-ordination increase the connectedness of actors both within and across arenas and thus radical product/process innovation?; (2) How is globalization impacting on national systems of innovation? Because of space limitations, we can only provide a brief discussion of these complex matters.

Co-ordination Modes, Connectedness and Radical Product/Process Innovation

A variety of modes of co-ordination shape the relationships among actors within and across arenas: markets, corporate hierarchies, the state, associations, and networks. Modes of co-ordination are important in our theoretical perspective, for they hamper or facilitate communication/connectedness among actors within and across arenas. Modes of co-ordination are conduits for facilitating communication among actors. While all of the above modes of co-ordination exist in most 'modern' societies, the literature demonstrates that one coordinating mode is usually more dominant than others in any particular economic sector (Hollingsworth and Boyer 1997; Kitschelt 1991). Indeed, in some societies, one mode of co-ordination is more dominant and pervasive than any other. The pervasiveness of the mode can be ascertained by the variety of different kinds of activities that are coordinated. However, markets tend not to provide the kind of tight connectedness both within and across arenas which is necessary for radical innovations. Because modes of co-ordination influence the degree of connectedness among actors within and across arenas, the specific non-market mode of co-ordination which is dominant in a particular sector/society plays an important role in influencing the kinds of radical innovations that emerge. While the state is an important coordinating mode in all economies, it is the dominant mode of co-ordination in only a few, but where this is the case, radical innovations emerge only in selective industrial sectors, as the case of France suggests. In some industrial sectors, the French state has been particularly successful in facilitating radical product innovations, evidenced by the development of a variety of military weapons, nuclear energy, high speed trains, and other market segments involving high outlays of capital and tightly linked but large, complex technological systems. The market segments in which the French state tended to be successful in facilitating radical product innovations were cases in which the state was both customer and supplier, and thus there was a strong connectedness across a variety of arenas. Several factors have influenced this kind of connectedness in France: (1) most of the relevant researchers have been civil servants trained in many of the same schools; (2) the state generally transfers researchers from one position to another, within and across organizations and arenas; and (3) finally, the technologies in these market segments change slowly. Some sectors require rapid, flexible, and effective communication among actors within and across arenas, if there is to be radical innovation. The state cannot generally provide this kind of rapid and flexible communication, but because the French state has been the key actor in several industrial sectors which require rapid and flexible co-ordination, the French economy has performed poorly in those sectors. These have included the following industries: semiconductors, biotechnology, numerical control machines (Cohen 1992).

In a society as large and as complex as the United States, some industrial sectors are dominated by one mode of co-ordination and others by another. Like the situation in France, when the American state has been both customer and supplier and there have also been requirements of large outlays of capital and the existence of tightly linked but large, complex, technological systems, there have also been radical innovations, e.g. industries involving nuclear energy, aircraft, and space technology.

In the United States, there is a fair degree of variation across sectors in the particular mode of co-ordination which is dominant. Throughout the twentieth century, corporate hierarchies have been a dominant form of co-ordination in many American industrial sectors. Significantly, a number of radical breakthroughs occurred in basic science and product development in industrial laboratories where researchers were tightly linked to each other as they addressed problems requiring a high degree of communication and complex and diverse scientific knowledge, e.g. Bell Labs, and the laboratories at Westinghouse, DuPont, Xerox. However, because the arenas of basic research and product development were frequently poorly linked to other arenas in the corporate organization, these companies often failed to benefit commercially from some of their most stunning radical innovations (Lynn et al. 1996). When corporate hierarchies were historically the dominant mode of co-ordination within a sector, radical innovations were successful when the different parts of the corporate hierarchy were tightly linked to each other (Hollingsworth 1991, 1997).

As suggested above, though, joint ventures and other forms of inter-organizational alliances have become increasingly important as a mode of coordinating actors, both within and across research arenas. In industrial sectors where the knowledge base has been both complex and rapidly changing, and where inter-organizational alliances have successfully promoted tight connectedness both within and across arenas, radical innovations have tended to emerge (e.g. biotechnology, computer software and hardware, and semi-conductors). This mode of co-ordination is becoming increasingly pervasive in industrial sectors, involving complex knowledge both within and across arenas (Malerba and Orsenigo 1993, 1997).

Another co-ordination mode that can facilitate radical innovations is associations. Of course, there are different kinds of associations, and they engage in a wide variety of coordinating activities (Schneiberg and

Hollingsworth 1990). Where associations are clearly one of the most dominant modes of co-ordination in an entire economy, there tend to be very complex rules pervading all industrial sectors, and these complex rule systems tend to hamper the kind of flexible and rapid change associated with most forms of radical product innovations. Because societies with associations which coordinate both labour and capital tend to promote high quality training and production facilities, such societies perform extraordinarily well in incremental product innovations (Hollingsworth 1997). On the other hand, a high institutionalization of associations — precisely because it promotes cooperation between labour and capital — can facilitate radical process technologies. Walton's (1987) analysis of the adoption of radical new process technologies in the loading and unloading of shipping vessels in several European countries is such an example. Radical process innovations can emerge in such an institutional environment, because strong associations on the parts of both labour and capital tend to promote high communication within the industrial relations system of such societies, thus facilitating a high degree of trust across the arenas of those sectors where associations are highly developed.

Thus far, our emphasis is on the importance of modes of co-ordination which are embedded in particular regional or national environments. However, there is some evidence that radical product and radical process innovations are also emerging from inter-organizational relationships, in the form of global alliances (Doz and Hamel 1998; Gomes-Casseres 1996). An interesting research question is whether these global alliances can overcome the friction created by physical distance which interferes with intense and frequent communication among actors both within and across arenas, a prerequisite for radical product and radical process innovations.

This discussion raises a rather critical and new line of research: How does the mode of co-ordination affect the strength of connectedness, and, in particular, the transfer of tacit knowledge within arenas and across arenas? Insofar as governmental policy is becoming increasingly concerned with the problem of stimulating industrial innovation, the question of how a specific mode of co-ordination influences the connectedness among arenas should emerge as a critical issue.

National Systems of Innovation versus Globalization

One of the most interesting modes of co-ordination is the global inter-organizational network, not only because such networks are increasing so rapidly, but also because they transcend national boundaries and attempt to connect actors across great distances (Harbison and Pekar 1998). It is these characteristics that pose the tension between national systems of innovation and the process of globalization. Indeed, our concepts about the size of arenas and the connectedness within and among arenas provide a way of approaching the current debate about the national systems of innovation vs. globalization. If one finds similar size arenas and similar degrees of connectedness within and among arenas across industrial sectors or market segments within a country, this provides some evidence for the existence of a national system of innovation (Campbell et al. 1991; Guerrieri and Tylecote 1998; Kitschelt 1991; Pavitt 1984). But can there be high connectedness within and across arenas when arenas cross national boundaries? In other words, how tight can trans-national connectedness be? Overall, our framework provides a way of thinking about globalization relative to radical product/process innovation networks. Is it possible to have both a national system of innovation and at the same time the globalization of some of the arenas involved in an idea innovation network? Our framework and its relevance for both national systems of innovation and globalization require some extended discussion in order to address this question.

The Thesis: National Systems of Innovation

Even though our analytic framework about idea innovation networks permits us to address the presence of national systems of innovation, we are not suggesting that all the richness of the concept of national systems of innovation can be captured either by the concepts of arena size and connectedness with and among arenas or by the concept of modes of co-ordination. Idea innovation networks are embedded in national systems of innovation which essentially consist of the institutional make-up of a society. Anyone familiar with the national system of innovation literature and the complementary one on social systems of production knows that there are a number of concepts — norms, modes of co-ordination, institutional sectors — which provide the glue holding actors together within these systems (Hollingsworth 1997; Whitley 1992a, 1992b), and because idea innovation networks are very much influenced by the institutionalist environment within which they are embedded, our perspective requires us to reflect on the linkage between idea innovation networks and the national systems of innovation.

A major issue that is difficult to resolve is the question of consistency in the patterns of idea innovation networks in a society. There is always some variation in arena size and in the degree of connectedness within and among arenas across industrial sectors in a specific society, if for no other reason than the complex nature of industrial sectors. At what point does this variation become great enough, so that one would conclude that there is not enough consistency in the idea innovation networks of industrial sectors to argue that there is no national system of innovation? Even if we do not have a precise answer to this problem at this time, our framework retains its utility, because of its potential for mapping and analyzing the innovation process.

The Antithesis: Globalization

Idea innovation networks not only vary across sectors, but some of these sectors have been impacted by global forces. Within the arenas of some market segments, there has been strong connectedness across national boundaries, as illustrated in the case of Korea's semi-conductor industry.

Airbus, the Boeing network, and the automobile industry, are but a few of numerous global strategic alliances (Gomes-Casseres 1996). Even when global strategic alliances are research-oriented, there is not yet enough data to determine the degree to which there has been strong connectedness in those arenas with cross-national boundaries, except in those instances where a new organization has been created to pool the researchers of different nations. Given the difficulty of creating tight connectedness across national boundaries, the success of globalization in creating radical product and process innovations has thus far been quite limited.

Most discussions of globalization have focused on issues very different from the idea of connectedness within an arena across national boundaries. One of the advantages of the framework posed here is it provides a new way of thinking about the impact of globalization on national systems of innovation. We are also confronted with the same methodological issue as when we study national systems of innovation. How many arenas of how many industrial sectors must be connected transnationally before one can determine that there is an innovation system operating at the global level? This issue is further complicated by the problem of the strength of connectedness: many of the transnational joint ventures tend to have low levels of communication among actors across arenas that cross national boundaries.

A Potential Synthesis?

We propose a solution for resolving these two perspectives. First, only some sectors are involved in global alliances and international joint ventures. There are many more sectors that are not. Second, there is the issue of whether or not the strength of the connectedness will continue. Once cross-national actors have completed their learning for solving particular problems, the necessity for the inter-organizational joint venture often diminishes.

When actors perceive that specific research arenas of an industry of their own society are not performing as well as those in another society, they often develop connectedness (e.g. joint venture, merger, licensing of products) with the actors in a better performing arena of a different society. Partly for this reason, research strategies in some market segments are becoming increasingly global in nature, but these relationships do not necessarily remain, unless a new permanent organization is created.

What has not adequately been studied is the degree of connectedness of the cross-national arenas and the role of various non-market co-ordination modes in facilitating the connectedness. One arena that appears to be more and more global is basic research (Petrella 1995). In this arena, there is considerable cooperative research across national boundaries, but major breakthroughs in this arena tend not to occur, unless the actors are in the same location and can have frequent and intense face-to-face interaction (Hollingsworth and Hollingsworth 2000).

One way of reconciling these perspectives is to recognize that the national system of innovation tends to influence the choices that actors make in how they connect with actors in foreign arenas. We are struck by the different choices made by South Korea and Taiwan, and these were influenced by the dominant mode of co-ordination within each country: corporate hierarchy in the former instance and a state-corporate hierarchy in the latter. Our judgement is that national systems of innovation have considerable persistence and are not likely to succumb in the short term, but the processes of global alliances do weaken national systems of innovation.

Recognizing that we are all nested in multiple levels (global, national, subnational regional, local) of reality, we should attempt to understand the connectedness and co-ordination of these multiple levels by having a specific research agenda which addresses these problems. One place to begin to comprehend this multiple-level world is to focus on the strategy proposed here: the study of the shape and outcome of research arenas and how they are connected and coordinated at the local, sub-national regional, national, and global levels.

Increasingly, the co-ordination of research arenas is occurring simultaneously at these various spatial levels; actors and arenas are nested in institutional arrangements which are connected and coordinated at several spatial levels. Because innovativeness at the local and the global levels are increasingly intertwined, one of the major challenges for the social science community is to comprehend the nature of this nestedness and the linkages which exist among arenas and actors at all of these different levels (Hollingsworth 1997). As we move ahead with the agenda of this paper, we should attempt to understand how various innovative processes are interlinked at both the global and local levels.

Conclusions

Our major objective in this paper has been to provide a new framework for thinking about radical product and radical process innovation. We have related the size of six arenas and the strength of connectedness within and among these arenas to a number of different literatures, namely those on organizational learning, inter-organizational networks, national systems of innovation, and modes of co-ordination. Our framework suggests what must be learned in different arenas and how they must be linked with other arenas if radical innovations are to occur. We have observed that this learning process is increasingly occurring in inter-organizational networks, some of which cross national boundaries. The extent to which this learning process occurs depends in part on the particular modes of co-ordination and on the national systems of innovation involved.

Our central thesis is that the strength of connectedness among diverse actors impacts on the amount of radical product/process innovation within and across arenas of industrial sectors. Radical solutions do not occur in each arena in a network where radical innovations occur. However, we are arguing that when a particular arena has a radical solution, it must be strongly connected with other arenas.

Our perspective on idea innovation networks relates to a problem currently high on the agenda of the social sciences: What is the capacity for societies to change, especially their institutions? Not only do institutional environments influence the structure of idea innovation networks, but changes in the idea innovation networks can feedback and bring about changes in a society's institutional environment. Of course, the forces which bring about institutional change are complex, but there are various indicators which suggest that in some societies, changes in the idea innovation networks are having some impact in changing a society's entire institutional landscape. Preliminary evidence suggests that changes in idea innovation networks have less impact on societal normative and rule systems, and more impact on their dominant modes of co-ordination and other parts of their social system of production.

In all advanced industrial societies, a virtual explosion in knowledge has occurred in the past two decades, which is expressed with many more researchers, more research expenditures, and greater innovative outcomes in the idea innovation networks of research intensive industries. Totally new academic disciplines are emerging in universities. As academic disciplines shape norms and rules for governing and ordering the behaviour of researchers, this in itself is an example of how the expansion of research arenas is bringing about changes in the institutional environment (Gibbons et al. 1994).

As expansion in the size of research arenas has occurred, the complexity of knowledge, materials, and products has also increased. This in turn has led to the development of numerous new organizations which exploit new knowledge by being highly specialized. Organizations which historically were very complex in their structure have been spinning off many of their divisions, creating more specialized products and organizations in the process. In the United States, hundreds of new organizations involving biotechnology and computer-related technologies have been created (National Science Foundation 1996).

With this acceleration in the development of new knowledge, thousands of new companies have emerged globally, organizations which are relatively specialized by arena. This process raises critical questions about how organizations with specialized arenas will be connected to and coordinated with other organizations and arenas. Years ago, Lawrence and Lorsch (1967) wrote about the problem of coordinating and connecting the numerous divisions and arenas inside an existing organization. In a number of contemporary societies, as larger firms are downsizing and as new organizations containing specialized arenas are emerging, there is now the problem of coordinating and connecting these organizations with each other. The problem of how to coordinate arenas is not a new one. What is different from the Lawrence and Lorsch perspective is the problem of coordinating and connecting organizations to each other (Hage and Alter 1997).

There is a long history of industrial districts in which there was a great deal of cooperation among organizations structured around specialized research arenas. Examples are found in the history of Emilia-Romagna in

Italy, Baden-Württemberg in Germany, and in various areas in southern France. In recent years, this co-ordination process has become quite prevalent in parts of Bavaria in Germany, California, Colorado, Massachusetts, North Carolina, Texas, and other parts of the United States. The number of industrial districts is increasing in part because of governmental policy and in part because of the spill-over of small high-tech companies, and as this occurs one observes many forms of networks becoming common as modes of coordinating research arenas. In some countries, the acceleration towards various types of networks represents a shift in how an economy is coordinated. For example, the United States, in which the co-ordination of research arenas was historically by markets and hierarchies, is now having that pattern altered as various forms of networks become more common in coordinating research arenas and conducting other types of economic activity (Pyke and Sengenberger 1992; Piore and Sabel 1984).

There are other examples of how the expansion of research arenas is feeding back to alter the institutional landscape of societies. In Bavaria, where there are serious efforts to compete with the biotechnology research arenas in America, policy makers are attempting to accelerate the scale of venture capital markets and to alter the rules for awarding individual workers within research arenas with stock options for meritorious service. In the United States, there have been efforts to modify the antitrust laws in order to permit competitors to engage in joint research in the same and different arenas (Casper 1999; Browning et al. 1995).

As long as societies have variability in their social systems of production, they will continue to vary in the shape and behaviour of their idea innovation networks. Societies will attempt to mimic one another in the development of their research arenas, but each society's social system of production is a configuration of a host of institutional arrangements (Hollingsworth 1997). Although each system is constantly changing and is open to influence from other systems, the direction of change is constrained by the society's existing social system of production, which has a great deal of historical specificity and persistence. Thus, the same research strategies and methodologies in the same arenas and the same industrial sectors but in different societies will have varying consequences.

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