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SOCIAL NETWORKS, LEARNING, AND FLEXIBILITY: SOURCING SCIENTIFIC KNOWLEDGE IN NEW BIOTECHNOLOGY FIRMS

Julia Porter Liebeskind
Amalya Lumerman Oliver
Lynne G. Zucker
Marilynn B. Brewer

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ABSTRACT

We examine how two highly successful new biotechnology firms (NBFs) source their most critical input -- scientific knowledge. We find that scientists at the two NBFs enter into large numbers of collaborative research efforts with scientists at other organizations, especially universities. Formal market contracts are rarely used to govern these exchanges of scientific knowledge. Our findings suggest that the use of boundary-spanning social networks by the two NBFs increases both their learning and their flexibility in ways that would not be possible within a self-contained hierarchical organization.

Julia Porter Liebeskind
Department of Management and Organization
School of Business Administration
University of Southern California
Los Angeles, CA 90089-1421

Amalya Lumerman Oliver
Department of Sociology and Anthropology
Hebrew University
Mount Scopus
Jerusalem
ISRAEL

Lynne G. Zucker
Department of Sociology
University of California, Los Angeles
Los Angeles, CA 90095-1551
and NBER

Marilynn B. Brewer
Department of Psychology
Ohio State University
1883 Neil Avenue
Columbus, OH 43210-1222

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1. INTRODUCTION

In a recent editorial, Daft and Lewin (1993) called for more midrange and grounded studies of the new flexible learning organizations that are currently displacing older bureaucratic and hierarchical structures in what they describe as an "organizational revolution." Commenting that "managers, not organization scholars, practice organization design and redesign," Daft and Lewin express concern that without grounded studies, organization theory will become "isolated and irrelevant." In response to Daft and Lewin's call, we examine how two highly successful new biotechnology firms (NBFs) use boundary-spanning social networks to source their most critical input -- scientific knowledge. Our findings suggest that the use of boundary-spanning social networks by these NBFs increases both their learning and their flexibility in ways that would not be possible within a self-contained hierarchical organization. However, in defense of hierarchy, we argue that the NBFs' own rules and procedures play a critical role in supporting their use of social networks.

2. ORGANIZATION AND COMPETITION IN THE BIOTECHNOLOGY INDUSTRY

2.1 Background

Biotechnology comprises three different technologies: recombinant DNA or "rDNA" technology, first discovered by Boyer and Cohen in 1973; monoclonal antibody, or "Mabs" technology, first discovered by Kohler and Milstein in 1975; and protein engineering technology, developed during the 1980s. Together, these three technologies offer the prospect of producing an array of highly valuable processes and products in areas such as human health, crop production and protection, chemical feedstock production and processing, food processing, and waste management. The *biotechnology industry* consists of firms involved in the research, development, and commercialization of such processes and products.

2.2 Organization of the biotechnology industry

The development of the U.S. biotechnology industry has been characterized by the founding of large numbers of new biotechnology firms (NBFs) dedicated to researching and developing new products. Powell and Brantley (1992) attribute the development of NBFs to the fact that biotechnology was a competence-destroying innovation for established firms in client industries such as pharmaceuticals and chemicals. Lacking an understanding of biotechnology, established firms channeled their investments in biotechnology research to NBFs through long-term contracts or by forming joint ventures (Arora and Gambardella, 1990; Pisano, 1990). NBFs, in turn, entered into long-term contracts with established firms to obtain such complementary assets as product testing, production, marketing and distribution capabilities that NBFs lacked at the outset of their development (Barley, Freeman and Hybels, 1992; Pisano, 1990; Powell and Brantley, 1992; Shan, 1990; Teece, 1989). Consequently, the biotechnology industry is characterized by a network structure of interorganizational alliances that govern the exchange of complementary assets among NBFs, scientists, and established firms. NBFs are central to these interorganizational networks of alliances because of their role as intermediaries between scientists, who make basic discoveries, and large firms that have established capabilities in product testing, production, and distribution, but which lack critical biotechnology knowhow (Barley, Freeman, and Hybels, 1992; Powell and Brantley, 1992). The survival and success of NBFs within the industry network structure therefore depends on their ability to capture rights to scientific knowledge in the form of commercially valuable discoveries made by scientists.

2.3 Competitive conditions in the biotechnology industry

The two NBFs we studied are both involved in the production of human health care products, including human diagnostic and therapeutic products, and associated treatment delivery systems. This industry segment is characterized by hypercompetition, compounded by appropriation problems, high levels of uncertainty, and critical resource immobility.

Hypercompetition: According to D'Aveni's (1994) criteria, the health care segment of the biotechnology industry can be classified as a "hypercompetitive" environment. Biotechnology itself is a revolutionary technology, and rapid technological innovation within biotechnology threatens to render even current biotechnological products obsolete within a relatively short time. Therefore, NBFs can sustain a competitive advantage only by continuous innovation that results in valuable and patentable products. The capacity of an NBF to achieve that goal depends critically on its supply of scientific knowledge. Meanwhile, the rapid pace of innovation in biotechnology demands that NBFs maintain strategic flexibility by minimizing their sunk cost investments in any particular line of research.

Uncertainty: Because biotechnology is a leading edge technology, NBFs cannot determine in advance if any particular research program in which they invest will lead to a valuable discovery. In some cases, biotechnology research has produced unique and highly valuable new health products.[1] In other cases, products that were expected to succeed have failed dramatically.[2] NBFs also face uncertainty about competitive conditions. New products developed by rival firms may render an NBF's research programs, or even its products, immediately obsolete. Meanwhile, the locus of innovation in biotechnology is constantly changing. University-based expertise is diffusing rapidly as new generations of biotechnology scientists are trained and move away from the early centers of innovation such as Stanford and UCSF (Kenney, 1986). New NBFs continue to be founded, often to capitalize on key discoveries from these new centers of university research (Zucker, Darby, and Brewer, 1994). The high levels of technological and competitive uncertainty make it extremely difficult for NBFs to determine which scientific knowledge is potentially commercially valuable and which is not.

Appropriability: The rapid pace of innovation in the health care sector of biotechnology is fuelled and accelerated by strict property rights regimes. According to United States patent laws, only firms that are first to discover a product or process can reap any financial rewards from it. Firms therefore have incentives to "race" for patents by intensifying their research efforts (Grossman and Shapiro, 1987; Lippman and McCardle, 1987). Each NBF faces numerous committed competitors in these patent races, including established firms, other NBFs, and potential new NBF entrants. Established firms fuel competition by using their deep pockets to fund their own research or to fund NBFs' research efforts (Arora and Gambardella, 1990; D'Aveni, 1994). Moreover, all NBFs can be expected to be intensely competitive because they are strategically dedicated to the biotechnology industry (Ghemawat, 1991; Porter, 1980). This intense competition for patentable knowhow in biotechnology creates incentives for rival firms to appropriate scientific knowledge that is not already protected by patent laws. NBFs must therefore guard against appropriation in sourcing scientific knowledge.

Intellectual resource immobility: Although the number of biotechnology scientists has increased rapidly in the last decade, only a few "star" researchers have made numerous commercially valuable discoveries, and many of these stars work in universities. For example, Zucker, Darby, and Brewer (1994) identify only 337 star researchers in biotechnology. Of the 213 stars in their sample who were trained in the United States, fully 163 (77%) worked in universities and another 44 (21%) worked in other non-profit research institutes; only six stars

(3%) worked in firms. Therefore, NBFs need to develop organizational arrangements that give them access to these valuable external intellectual resources.

In all, the biotechnology industry is an extremely challenging, hypercompetitive environment for NBFs. To survive and succeed, NBFs must devise organizational arrangements that enable them to source their critical input -- patentable scientific knowledge -- at minimum sunk cost while overcoming problems of uncertainty, appropriability, and intellectual resource immobility.

3. SOCIAL NETWORKS IN THE BIOTECHNOLOGY INDUSTRY

3.1 Hierarchies, markets, and social networks

We consider three organizational options available to NBFs for sourcing scientific knowledge: internal sourcing through the use of hierarchy, external sourcing through market exchanges, and external sourcing through social networks.[3] Transaction costs economics traditionally has distinguished between only two types of organizational arrangements for conducting exchanges: markets and hierarchies (Coase, 1937; Williamson, 1975). Markets organize the firm's external exchanges through price mechanisms and/or legal contracting; hierarchy organizes the firm's internal exchanges through direct employment and asset ownership (Camagni, 1989; Masten, 1988; Reve, 1990; Teece, 1989).

A common critique of this traditional analytical framework is that it ignores the importance of social values in the exchange process (Granovetter, 1985). Both "markets" and "hierarchies" are social constructions whose existence and efficacy depend on broad social consensus about norms of behavior. (See, for example, Belshaw (1965) and Geertz (1978).) Hence, exchanges in both markets and hierarchies can be understood to be both supported and shaped by the norms of the social groups involved (Dore, 1983; Granovetter, 1985). In some situations, social norms supplement the operation of markets and hierarchies. In other situations, social norms may actually substitute for markets or hierarchies in the organization of exchange. For example, Ouchi (1980) identifies three distinct types of organization for conducting exchanges: markets, bureaucracies, and "clans." In clans, shared norms and values ensure fairness in exchange without resort to market pricing, contracts, or managerial authority. In a similar vein, Bradach and Eccles (1989) define price, authority, and "trust" as alternative methods of supporting exchange, where trust is engendered by shared norms. Powell (1990) argues that exchanges through social networks constitute a separate and distinct form of organization in which exchange is predicated on trust. According to these definitions, and following the theoretical frameworks of Coase (1937), Masten (1988), and Williamson (1991), we can distinguish social networks from markets or hierarchies as a means of governing exchanges by two criteria:

1. Unlike hierarchies, but like markets, social networks involve *exchanges between legally distinct entities*. Network exchanges, like market exchanges, are external to the firm (Reve, 1990).
2. Unlike markets, but like hierarchies, *social networks support exchanges without using competitive pricing or legal contracting*. Specifically, exchanges between individuals or organizations that are conducted through social networks have no need for price competition or legal contracts because the shared norms of the exchange partners alone will ensure that outcomes are fair.

Shared norms of trustworthy behavior may be instilled through socialization and tradition among members of a specific social group such as a tribe, social class, region, profession, religion, industry, or organization (Brusco, 1982; Dore, 1983; Elster, 1989; Ross, 1906; Zucker, 1986). Norms of trustworthy behavior may also evolve over time as exchanges are repeated between friends or members of the same social group (Axelrod, 1984; Kreps, 1990). In addition, trustworthy behavior may be elicited by such mechanisms as posting a bond, testing, or performance monitoring, all of which are commonly used conditions of membership of professional or social groups (Evans-Pritchard, 1940; Klein and Leffler, 1981; Williamson, 1979). Therefore, a social network can be defined as *a collectivity of individuals among whom exchanges take place that are supported only by shared norms of trustworthy behavior.* Social networks may or may not be contiguous with the boundaries of legally defined organizations. We describe a social network that includes members of more than one legally defined organization as a "boundary-spanning" social network.

3.2 Social networks, learning, and flexibility

According to Powell (1990) and Zucker (1991), social networks may make an important contribution to organizational learning. Powell (1990) argues that social networks are the most efficient organizational arrangment for sourcing *information* because information is difficult to price (in a market) and to communicate through a hierarchical structure. He states (p. 304):

> Networks are particularly apt for circumstances in which there is a need for efficient, reliable information. The most useful [valuable] information is rarely that which flows down the formal chain of command in an organization, or that which can be inferred from price signals. Rather, it is that which is obtained from someone you have dealt with in the past and found to be reliable. You trust information that comes from someone you know well.

Powell's argument is that social networks serve as sources of reliable information, which is essential to efficient organizational learning. Hence, organizations whose employees are members of a social network would learn more efficiently than organizations whose employees are not members of a social networks, because the quality of the former's information would be higher. That may be particularly true when social networks span the boundaries of the firm. According to Zucker (1991, p. 164) bureaucracies (i.e., firms) often lack "expert" information and must therefore seek it externally:

> While bureaucratic authority is by definition located within the firm's boundaries, expert authority depends on the information resources available to an individual, and not on the authority of office. Thus, authority may be located within the organization......but when an external [expert] authority market can provide information that leads to greater effectiveness, then [expert] authority tends to migrate into the market.

In addition, if expert authority is external to a firm, sourcing knowledge through social networks may enable the firm to integrate that knowledge more effectively than information acquired through market arrangements such as licensing, which do not allow for learning-by-doing or open-ended learning (Grant, 1996).

Social networks may also enhance flexibility -- a firm's capacity for responding to unpredictable changes in its competitive environment (D'Aveni, 1994; Volberda, 1996). Each time a firm internalizes and routinizes an activity, it makes a sunk cost investment in organization that is specific to that activity. When technology is changing rapidly, the value to a firm of undertaking certain activities and/or certain combinations of activities will also change rapidly; internalization therefore may result in excess sunk costs that are avoided in external exchanges (Camagni, 1989; Teece, 1989). In addition, rapid technological change undermines firms' ability to assess the value of information accurately because they cannot learn and institutionalize appropriate assessment routines in short periods of time (Camagni, 1989). An external "informational network" of experts can provide the firm with multiple evaluations of the value of its own information and knowhow, thereby increasing its efficiency in searching for valuable information, screening information, codifying information for managerial use, selecting appropriate investments, and applying managerial control (Camagni, 1989; Zucker, 1991). Therefore, sourcing information from external experts not only increases learning, but also increases the flexibility of a firm's boundaries because each external expert represents a "strategic sourcing option" that the firm can exercise only when necessary (Volberda, 1996).

3.3 Social networks in biotechnology

All NBFs have the option of sourcing scientific knowledge through the social network of academic scientists, because typically they are founded and staffed by university-trained scientists. For example, Herbert Boyer, a founder of Genentech, is one of the discoverers (and patenters) of gene-splicing technology and is a renowned academic scientist (Kenney, 1986).

Consistent with Powell's (1990) arguments, the social network of academic scientists is characterized by norms of trustworthy behavior in exchanges of information. Indeed, the network exists to ensure the reliability of scientific information (David, 1991; Merton, 1973). Among academic scientists, these norms are well defined and socially enforced, and include reciprocity, respect for individuals' intellectual property rights, and honesty in research (Blau, 1973; Crane, 1972; Merton, 1973; Nelkin, 1984). Individual scientists' intellectual property rights are protected through presentations and authorship of published research reports. Norms of honesty in research are instilled through long and rigorous training and are enforced through research that seeks to replicate and validate the findings of other scientists (David, 1991; Merton, 1973). Reputations for trustworthy behavior can be established in the social network because academic scientists conduct repeated exchanges of information through shared research programs, attendance at meetings, presentations, and reviewing and refereeing written work (Merton, 1973). The system of repeated exchange allows detection and punishment of plagiarism and falsification (Klein and Leffler, 1981). Finally, scientists who do not conform to accepted norms can be excluded from exchanges of information (such as participation in research teams and access to the latest research findings), which will severely damage their future careers (Crane, 1972; Merton, 1973). In extreme cases, plagiarism or falsification of research findings will lead directly to job loss. In sum, trustworthy behavior among academic scientists is instilled, motivated, and maintained through a variety of mechanisms. Such behavior facilitates both the production and sharing of reliable, valuable information, allowing the frontier of knowledge to advance rapidly and at minimal cost.

Given the competitive conditions in the biotechnology industry, and given that social networks can increase organizational learning and flexibility, NBFs might be expected to depend heavily on the social network of academic scientists in sourcing scientific knowledge. First, by sourcing scientific knowledge from a wide variety of external scientists and organizations, an NBF can increase the likelihood that it will be the first to gain access to, or knowledge about, new discoveries. Sourcing knowledge externally through a social network rather than a market may also increase the reliability of externally acquired scientific knowledge (Powell, 1990). Not only will that knowledge be subject to the norms of scientific enquiry, it will also be sourced by the NBF's own experts -- its scientist-employees. In addition, when an NBF's scientists conduct collaborative research with external scientists, the latters' knowledge is integrated directly into the ongoing R&D program of the NBF, something that could not be achieved with pure market exchanges (Cohen and Levinthal, 1990; Grant, 1996).

Second, social network exchanges enable NBFs to reduce their costs. Such exchanges give NBFs access to cutting-edge research in universities that is funded by taxpayers, reducing the firm's sunk R&D costs (DeBresson and Amesse, 1991; Teece, 1989). By seeking evaluations from external experts, NBFs can better evaluate their own research programs and further avoid excess sunk costs of R&D (Camagni, 1989). In addition, using social networks eliminates the costs of using markets. Contracts are costly to negotiate, may involve substantial commitments of specialized resources, and may impose high costs of exit or renegotiation (Ghemawat, 1991;

Williamson, 1991). Such costs can be avoided when exchanges are conducted through social networks, which allow an NBF to be flexible in terms of switching from one external supplier of scientific knowledge to another as competitive and technological conditions change.

Third, social networks may provide more protection against appropriation than markets, where even legal contracting may not prevent misappropriation (Arrow, 1962; Levin et al., 1987). For example, some knowledge that is contributory to the discovery process may not be patentable. In addition, patent coverage may be too slow and/or too narrow to prevent appropriation of knowledge that can lead to follow-on products (Levin et al., 1984). Under such circumstances, the norms of scientists may protect an NBF against appropriation of unprotected knowledge. However, appropriability concerns may impel NBFs to govern certain knowledge exchanges exclusively through their own hierarchies if the returns to appropriation are so high as to render any external exchange risky. In particular, as research programs progress, their value becomes more certain, reducing the marginal value of external inputs of scientific knowledge, whereas the incentive for appropriation increases. By internalizing exchanges of more certainly valuable knowledge, an NBF can use managerial authority to restrict the flow of that knowledge beyond its boundaries. An NBF also increases the likelihood that it can establish undisputed property rights if it is the undisputed locus of discovery (Von Hippel, 1982).

Finally, social network exchanges may enable an NBF to gain access to unique resources. Expert knowledge that is critical to an NBFs' survival and success may be produced by scientists who are not willing to work for any firm and who cannot sell their research services through market contracting. In particular, many universities restrict the amount of time their employees can work for other institutions and/or the amount of income they can receive from outside sources (Giamatti, 1982; Kennedy, 1982). However, university scientists may be willing and able to supply scientific knowledge to an NBF through scientific collaboration, if they can receive resources in return to satisfy norms of reciprocity (Mauss, 1950; Ouchi, 1980; Zucker, 1991). An NBF may also be able to attract and retain more talented scientists itself if it permits its employees to participate in external exchanges of scientific knowledge. Such external exchanges enable an NBF's scientist-employees to continue to gain prestige and friendships from their professional social network, reducing divergence between scientists' goals and those of the organization (Deutschman, 1994). In turn, increasing the status of an NBF's scientist-employees in the social network of scientists through research exchanges has the potential to increase the number and importance of external exchanges an NBF can enter into.

In sum, an NBF can benefit substantially from supporting and promoting external exchanges of scientific knowledge, especially those conducted through social networks, so long as the benefits of those exchanges are greater than any costs of misappropriation that might result.

4. METHOD

4.1 Sample

This study describes the organizational arrangements used to source scientific knowledge in two highly successful NBFs -- firms that have succeeded in sourcing and commercializing valuable scientific knowledge. As both firms requested anonymity, we refer to them as Firm X and Firm Y. Both firms are involved in the most profitable segments of the biotechnology industry: human therapeutic and diagnostic products. In some product markets the two firms are head-to-head competitors. In addition, the two firms are diversified into similar numbers of different product areas. The firms operate under identical regulatory and property rights regimes. The products of both firms are biomedical products that are governed by FDA regulations, and most of their products are patentable under U.S. intellectual property laws. Both firms are located in California.

We used a sample of only two firms because collecting data on social network exchanges is difficult and time-consuming. Our approach therefore represents a choice of depth over breadth. We chose to study two firms with similar transactions, operating under similar regulatory regimes, to provide some comparison of our findings and theoretical interpretations. The data we report detail each firm's organizational arrangements for its supply of scientific knowledge after its founding; we have 10 years of data for Firm X and nine years of data for Firm Y. To preserve the two firms' anonymity, the year of founding of each firm is designated as year 1. The two firms were founded relatively closely in time, so their development is unlikely to have been differentially influenced by changes in their competitive environments over time.

4.2 Data and measures

We considered three alternative organizational arrangements for governing the exchange of scientific knowledge: hierarchies, markets, and social networks. We measured both organization-level and individual-level exchange arrangements.

Although ultimately all exchanges of knowledge take place between individuals (Grant, 1996), individual-level exchanges can be supported by organization-level arrangements. We classified exchanges that take place between individuals who are scientist-employees of the same NBF as being governed by the firm's hierarchy, because a firm's managers are legally empowered to establish and enforce terms and conditions of employment (Masten, 1988). We classify "market" exchanges as (1) exchanges between the scientist-employees of an NBF and employees of other organizations with which the NBF has some type of formal contractual agreement for the supply of scientific knowledge or (2) exchanges between the scientist-employees of an NBF and individuals (a) who are not employees of the firm and (b) are not employees of any other organization with which the NBF has some type of formal contractual agreement for the supply of scientific knowledge, but (c) are parties to a formal, legally enforceable, individual contract with the NBF for the supply of scientific knowledge. Finally, consistent with our preceding definition, we classify "social network" exchanges as exchanges of scientific knowledge between scientist-employees of an NBF and individuals who are not employees of the firm or of any other organization with which the NBF has some type of formal contractual agreement for the supply of scientific knowledge, and who are not parties to any formal, legally enforceable, individual contract with the NBF.

We measured exchanges of scientific knowledge in terms of scholarly publications on which scientists at the two NBFs studied were named as authors. Scholarly publications measure the production of scientific knowledge because research findings are published only if they are considered to contain valid, reliable information that is of value to other scientists (Martin and Irvine, 1985). Publication data also provide impartial records of patterns of scientific collaboration at the invidual level, and of knowledge production at the individual and institutional level (Irvine and Martin, 1985; Zucker, Darby, Brewer, and Peng, 1995).

Possibly, not all research collaborations conducted by scientists at a firm lead to knowledge that is directly useful *to that firm*. For example, scientists who have discretion to design their own research programs may choose to conduct research that interests them rather than reserach that meets the goals of the firm. We have no direct data on the "usefulness" of the research collaborations we measured. Indeed, "usefulness" may be impossible to measure: discoveries (and their associated patents) typically emerge from long programs of research, and the contribution of publications to the development of scientific knowledge necessarly varies (Irvine and Martin, 1985). Interviews conducted at Firm X and Firm Y suggested that collaborative research between employee-scientists and external scientists served several purposes. Some collaborative research represented a continuation of ongoing research programs between scientists who had joined the two firms and their colleagues who had remained at universities. Much of this research was evidently valuable to the two firms because it was the reason for their employing these scientists in the first place. In addition, some external collaborative research was strategic, in the sense that key external scientists were sought out to work on specific problems that the firms themselves lacked the resources or knowledge to pursue, consistent with Zucker's (1991) arguments. Finally, some external research collaborations were "prospecting," allowing the firms to "peek" at others' knowledge at low cost, consistent with the arguments of Camagni (1989) and Teece (1989). Although much of the last type of research may not prove useful, both firms encouraged prospecting research collaborations in the expectation that some would pay off in the future.

We recognize that using publication data provides an incomplete measure of exchanges of scientific knowledge at Firms X and Y. First, publication data exclude information on research collaborations that did not yield publishable results, even though that outcome may have provided valuable information to the two firms (e.g. a line of research is not worth continuing). Conversely, a collaboration may have provided knowledge so valuable that the NBF withheld it permanently from publication. Second, scientific knowledge can be exchanged in ways other than through research collaborations. For example, scientists at both firms attend scientific meetings and colloquia both at their own firm and at outside institutions (Martens and Saretzki, 1993). However, much of the knowledge exchanged in that way may be of limited value to any individual firm because it is publicly available and so cannot be patented.

Firms X and Y both keep detailed records of scholarly publications in which their scientists are listed as authors. Using these records, we looked up the original articles in libraries and recorded each institution of origin of each external author as listed on each article. We were then able to compile data on the number, identity, and type of institutions at which external collaborating scientists worked. We also recorded the number of scholarly publications in which scientists at Firms X and Y did not collaborate with outside scientists. Altogether, these publication data enabled us to examine each firm's research exchanges in terms of the extent and frequency of research collaborations between scientists at Firms X and Y and external scientists, the number of external institutions involved in the collaborations, the types of institutions involved, the frequency of collaborative research endeavors with specific institutions, the degree to which the two firms' external exchange networks overlap, and the evolution of external research collaborations over time.

We gathered patent data from the *U.S. Patent Data Base* and from individual patent listings for the purpose of identifying the assignees of each patent. Additional patent data were obtained from corporate records. Data on patents were used only if the public and corporate records matched; sometimes patents that had been applied for but were not yet granted were listed in the corporate records.

The data were collected during the period 1989 to 1992. In addition to collecting proprietary data from the corporate records of the two firms, we obtained data from interviews with scientists and managers in the two firms, from public data sources such as the *North Carolina Biotechnology Database, BioScan,* the *Wall Street Journal Index*, and from various reports on the biotechnology industry published by consulting or investment firms such as Ernst & Young, Kidder Peabody, and Shearson Lehman.

5. EVIDENCE

5.1 Interorganizational arrangements

The extent of inter- and intraorganizational governance of exchanges supplying scientific knowledge to Firms X and Y is shown in Tables 1, 2, and 3. Table 1 gives the number of scientists directly employed by Firms X and Y. Firm X employed 197 scientists by year 10 and Firm Y employed 146 scientists by year 9. These numbers indicate that each firm was making substantial direct investments in intellectual resources that could be governed by its own hierarchy. Table 1 also shows that, despite the newness of the two firms, 47% of scientists at Firm X and 35% of scientists at Firm Y had been employed for five or more years. This finding indicates that the hierarchies of the firms supported long-term employment which is critical to building organizational learning and knowledge integration routines (Grant, 1996).

Table 2 provides evidence on the market arrangements of Firm X and Y for sourcing scientific knowledge. Panel A shows that both Firm X and Firm Y had numerous market arrangements. However, panel B shows that very few of those arrangements provided for knowledge sourcing: Firm X had only two knowledge-sourcing arrangements by Year 10 and Firm Y had only six by Year 9. Of the eight arrangements, five were long-term R&D contracts; there was only one R&D joint venture, one equity investment in another research-based firm, and one licensing agreement. This evidence is somewhat surprising. Previous studies show that NBFs are imbedded in a dense network of interorganizational market agreements for sourcing complementary assets (Barley, Freeman, and Hybels, 1992; Powell and Brantley, 1992). Moreover, Barley, Freeman, and Hybels (1992) found that 30.5% of the 2,206 alliances they studied were R&D alliances, but did not distinguish between R&D alliances in which NBFs *source* scientific knowledge from other organizations and those in which NBFs *supply* scientific knowledge to other organizations. Our data suggest that NBFs make very few market arrangements for sourcing scientific knowledge. At the organizational level of analysis, therefore, our data appear to suggest that Firms X and Y are almost entirely self-sufficient in terms of sourcing scientific knowledge. However, the evidence on individual-level exchanges leads to a different conclusion.

5.2 Individual-level exchanges of scientific knowledge

Table 3 reports the extent of individual exchanges of scientific knowledge at Firms X and Y, measured in terms of counts of published research findings. The table shows that scientists at both firms were highly involved in research that resulted in published research findings. At Firm X, scientists had produced 503 research publications by year 10; at Firm Y, scientists had produced 345 research publications through year 9. In both firms, a large number of publications involved scientists from other institution; 257 collaborations at Firm X and 256 at Firm Y involved external scientists. In addition, Table 3 shows that these external collaborations represented a large number of external institutions. Scientists at Firm X were involved in reseach collaborations with scientists at 144 different external institutions; scientists at Firm Y took part in research collaborations with scientists at 147 different external institutions. These large numbers of collaborations and external institutions illustrate the very high degree to which both firms relied on scientists to increase the scope of their organizational learning and to increase their strategic and organizational flexibility. They are also supportive of the argument that NBFs "prospect" for valuable scientific knowledge at many different institutions to reduce uncertainty about the loci of innovation, and to discover valuable scientific knowledge that they can subsequently absorb.

Remarkably, almost none of the external exchanges of scientific knowledge entered into by Firms X and Y were governed by contracts or other market mechanisms. Only two publications involved institutions with which Firms X or Y had an interorganizational contract, and no exchanges were governed by individual-level contracts. The reason for this result may have been that most of the external exchanges involved scientists at universities and other non-profit research institutions where contracting restrictions apply: Table 4 shows that 86% of all institutions involved in published collaborative research with Firms X and Y were universities and other non-profit research institutions. Moreover, panel B shows that the rates of collaboration per institution were far higher for external universities than for external firms. This finding suggests that the two NBFs were willing to conduct a large number of external collaborations at a large number of different institutions, governed only by the norms of the scientific social network. In addition, Table 4 shows that many scientific collaborations at Firms X and Y involved scientists outside the boundaries of U.S. jurisdiction on intellectual property rights; 29% of all institutions participating in collaborative research with Firm X and 43% of all institutions participating in collaborative research with Firm Y were located outside the U.S.

By way of caveat, we note that material market exchanges often exist on the level of individual scientists, including payment for consulting and Scientific Advisory Board membership as well as for research materials. In later work, Zucker, Darby, and Armstrong (1994) report that a survey of top California bioscientists indicates that payments for services or equity participation is nearly universal in their collaborations with NBFs. Furthermore, subsequent to our case studies, one of the firms introduced a requirement for an explicit contract establishing intellectual property rights with every external scientist involved in a collaboration.

Table 5 provides further evidence of the "prospecting" nature of external collaborations at Firms X and Y. Very few of the external research collaborations conducted by the two firms produced numerous publications, which are an indication of a long-lived research program. At Firm X, 130 of a total of 144 (90%) collaborative research relationships by yielded five or fewer research publications; in Firm Y, 134 out of 147 (91%) collaborative relationships yielded five or fewer publications.

Other studies have shown that NBFs decrease their number of market agreements involving complementary assets over time (Kogut, Shan, and Walker, 1992; Shan, 1990). Therefore, we investigated whether Firm X and Firm Y became more autonomous in terms of research capabilities over time. The evidence in Table 6 shows that annual rates of external research collaborations at Firms X and Y did not decline with time during the period studied. At Firm X, scientists steadily increased their number of external collaborations over time to a high of 62 collaborations in Year 10; at Firm Y, scientists maintained a rate of about 40 external collaborations from Year 5 onwards, although the rate fluctuated from year to year. This evidence suggests that Firms X and Y continued to gain benefits from research collaborations during the period studied in terms of prospecting for innovations, reducing thier direct R&D costs, accessing the knowledge of immobile external scientists, and attracting and retaining scientist-employees. Table 6 also shows that scientists at Firms X and Y continued to publish their own research findings, even when research did not involve collaboration with external scientists. However, the two NBFs differed in the degree to which they encouraged (or permitted) their employee-scientists to enter into network exchanges of scientific knowledge that did not involve external collaborations. The number of publications at Firm Y involving only its own scientists (n =89) was far lower than the number at Firm X (n =246), even though the numbers of external collaborations in published research were essentially identical for the two firms.

One question raised by this evidence is whether conducting numerous external research collaborations without the protection of legally enforceable contracts covering intellectual property rights led to appropriability problems for Firms X and Y. Table 7 shows that both Firm X and Firm Y obtained clear property rights to scientific discoveries during the period studied. Of the 28 patents owned by Firm X, only three were shared, none of them with scientists or institutions in their collaborative network. Of the 21 patents owned by Firm Y, two were shared with institutions with which the firm conducted collaborative research. However, Firm Y also had market agreements with those two institutions that may have specified that intellectual property be shared. Perhaps the reason for the lack of shared patents at Firms X and Y was that only "basic" (i.e., not commercially relevant) research was conducted with external scientists through social networks. In the case of biotechnology, however, basic scientific discoveries and commercially valuable products are typically indistinguishable. We therefore believe the evidence at least partially supports of the interpretation that the norms of the social network of professional scienists protect against the risk of knowledge appropriation.[4]

6. DISCUSSION

The evidence presented in the preceding section shows that social networks play an important role in promoting organizational learning and in fostering organizational flexibility in the two NBFs studied. Using a very wide network of external scientist-collaborators, Firms X and Y were able to access scientific knowledge at numerous institutions in the United States and abroad, increasing both their organizational learning and their operational and strategic flexibility.

Our findings suggest that social network exchanges make two important contributions to organizational learning. First, they contribute by extending the *scope* of organizational learning. The two NBFs sourced knowledge from a large number of other institutions. The reliability of this externally sourced knowledge was ensured by that fact that it was exchanged among members of the same social network (Powell, 1990) and by the fact that it was sourced by the firms' own experts -- scientist-employees (Zucker, 1991). Second, social networks contributed to the *integration of knowledge* at the two firms. Because collaborative research took place at the operating (research) level of the two NBFs, the knowledge held by external experts could be integrated directly into the routines of the firm. Indeed, the evidence is consistent with Grant's (1996) argument that, because all learning involves collaboration between individuals, markets are not good mechanisms for transferring knowledge. We find that almost none of the individual-level exchanges of knowledge through research collaborations involved organizations with which either NBF had a market agreement. In his study, Grant (1996) considers only firms and markets as alternatives for integrating knowledge. Our study suggests that social networks also warrant serious consideration as mechanisms for organizing the transfer and integration of knowledge between both individuals and organizations.

Our findings also illustrate how social networks can contribute to organizational flexibility. Volberda (1996) characterizes flexible firms as being able to adapt rapidly to changing circumstances at the operating, organizational, and strategic levels. Social networks can be considered to have increased the *operating flexibility* of the two firms. Because social networks in the two NBFs supported collaborative research, they facilitated the integration of new scientific knowledge into the two firms' operations through learning-by-doing. Also, social networks can be considered to have increased the *organizational flexibility* of the two NBFs by enabling them to switch from one source of knowledge to another without incurring the costs or commitments inherent in either hierarchical or market exchanges. Finally, using external sourcing of scientific knowledge permitted the firms to reduce the costs of their own hierarchies, which is essential to maintaining *strategic flexibility* in a rapidly changing industry characterized by high sunk costs (Camagni, 1989; Teece, 1989).

The evidence we report in this paper highlights the importance of social networks in sourcing scientific knowledge, but the importance of the two firms' own hierarchies in supporting those exchanges must not be overlooked. During the early stages of their development, Firms X and Y were both staffed and managed by academic scientists who imported the norms and values of academic science into the two firms. From the outset, therefore, norms of external collaboration were implanted in each firm as a core practice. In addition, each NBF's staff of highly skilled research scientists could initiate and support social network relationships with key external scientists (Cohen and Levinthal, 1990). To attract and retain such scientists, however, each NBF needed to maintain a "university-like" organizational context as it developed. That is, the NBF's organizational policies had to support both the formation and maintenance of boundary-spanning social network relationships as well as numerous other complementary activities such as rapid publication of research results and freedom of scientific inquiry (Deutschman, 1994). Therefore, the hierarchies of Firms X and Y clearly played a critical role in supporting and governing their internal exchanges is ways that supported their external exchanges, and vice-versa (Reve, 1990). This model is illustrated in Figure 1.

Daft and Lewin (1993) observed that new flexible learning organizations are replacing "structures that provide central control over activities." However, that change does not imply that the hierarchy of the firm is no longer important. Rather, our results suggest that the role of hierarchy in new learning, flexible organizations such as NBFs has shifted from *coordinating the on-going internal activities of the firm through a command and control structure* to *providing appropriate organizational support for both the internal and external exchanges* that are essential to the firm's survival and success. Indeed, providing such support may be *the* critical capability for knowledge-based firms (Adler, 1989; Henderson and Cockburn, 1994). In all such firms, self-coordination among experts is more efficient than coordination by managers (Thompson, 1967). However, self-coordination across organizational boundaries cannot take place without (at the very least) organizational permission or (at the very best) active organizational support.

One question that must be addressed is whether our findings are generalizable to other NBFs. We know of no other study that has examined the role of boundary-spanning social networks in biotechnology firms in detail. However, Kenney (1986) and Zucker, Darby, and Brewer (1994) argue that ties between NBFs and major research universities are an essential condition for NBF founding and survival. In addition, several studies suggest that market-type alliances are critical to the survival and success of NBFs. For example, Shan (1990), Kogut, Shan, and Walker (1992) and Oliver (1993) find that NBFs tend to form more interorganizational market-type alliances when they are newer and otherwise more likely to fail (Singh, Tucker, and House, 1986). Our findings suggest that social networks should also be considered in the calculus of NBF survival. In addition, our findings point towards an explanation for the failure of established pharmaceutical firms to enter biotechnology directly (Arora and Gambardella, 1990): those firms lacked access to the social networks that are critical to sourcing scientific knowledge. Deutschman (1994) argues that historically, large pharmaceutical firms discouraged their scientists from publishing research findings and therefore had difficulty attracting and retaining top scientists from academia. Yet without such scientists, access to social networks in biotechnology would be blocked and the absorptive capacity of the firm would be undermined (Cohen and Levinthal, 1990). Consequently, it is possible that large pharmaceutical firms could enter biotechnology only via strategic alliances with NBFs which were able to support social network exchanges of scientific knowledge.

An additional question that must be addressed is whether our findings are generalizable outside California, where both Firm X and Firm Y are located. California has provided a fertile breeding ground for new firms in several industries including biotechnology and electronics. Saxenian (1994) argues that the Silicon Valley area in particular has provided an exceptionally munificent environment for knowledge-based firms because the area's culture supports free exchanges of ideas. Possibly, NBFs located elsewhere in the United States may have different patterns of social network exchanges. However, Firms X and Y conducted social network exchanges with many institutions outside California, and even outside the United States, reducing the strength of the argument that biotechnology collaborations are regionally embedded. We believe it more likely that scientific collaborations in biotechnology are culturally embedded within the social network of professional scientists, wherever those scientists are located.

Our findings may also be generalizable to other emerging industries that depend on university research. Evidence shows social networks to be critical in certain industries such as publishing (Coser, Kadushin, and Powell, 1982) and investment banking (Eccles and Crane, 1988), but few industries at present are as embedded in the social network of academic science as biotechnology. Universities are now on the cutting edge of research in several other areas that hold great commercial promise, such as materials engineering. Our findings suggest that social networks will play a critical role in giving firms access to this new university-based knowledge.

Two emerging trends may change patterns of social network exchanges in biotechnology in the future. One is change in the locus of innovation. Many of the pathbreaking discoveries in biotechnology are now being made within firms. For example, Genentech is now ranked fourth in number of citations among all research institutions in genetics and molecular biology, ahead of prestigious research universities such as Harvard, Princeton, and MIT (Deutschman, 1994). If this trend continues, the reliance of many NBFs on universities for scientific knowledge may decline, reducing the importance of access to, and participation in, social networks. The second trend that may change current patterns of exchange is increasing awareness of the value of scientific knowledge. When biotechnology was in its infancy, the potential value of biotechnology products was highly uncertain. As more products are brought to market, much of this uncertainty is being resolved -- many products are proving to be very valuable. In an interview, the research director at one of the two firms we studied remarked that the firm was intending to introduce contracts to govern certain external research collaborations involving knowledge, materials or technologies that were highly valuable to the firm. At the same time, universities are becoming more vigilant in protecting their intellectual property rights, placing additional restrictions on, and increasing the costs of, flows of valuable scientific knowledge from universities to firms.[5]

We see several promising avenues for further research. First, our study did not examine the processes whereby scientists in NBFs form relationships with external scientists, or how such boundary-spanning relationships evolve over time.[6] It would be particularly interesting to investigate what organizational policies NBFs have in place to promote the creation and development of boundary-spanning social networks. Second, our study provides evidence that the social networks of Firms X and Y are global in scope, which raises questions of how long-distance collaborative relationships are formed, maintained, and governed. We hope that future research on social networks in biotechnology will address these issues.

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ENDNOTES

1. For example, the drug Neupogen (produced by Amgen Inc.), which is uniquely able to reduce anaemia in chemotherapy patients, had sales of $544 million in 1992 *(Business Week*, April 26, 1993, p. 86).

2. For example, the failure of Cetus Inc. is commonly attributed to its strategy of concentrating its R&D efforts on interleukins: In 1990, the FDA failed to approve the firm's product interleukin-2 as a treatment for cancer. (The firm was subsequently rescued by being taken over by Chiron Corporation which profited from the eventual success of products in Cetus's pipeline.) Genentech's "wonder drug" TPA, designed to treat thromboses, proved to afford little more benefit than established treatments, although it was far more costly. In 1993 and 1994, the FDA failed to approve several toxic shock treatments developed by Centocor and other NBFs, causing their market value to drop dramatically.

3. A distinction can and should be made between social networks as an *exchange governance mechanism* and *network structures* of exchanges that describe exchange patterns at the individual, organizational, industry or societal level. We use the phrases "social network" and "network" interchangeably to describe an *exchange governance mechanism*: a definition is given at the end of this subsection. Also note that we use the term "hierarchy" to describe governance of exchanges within a firm, following Coase (1937) and Williamson (1975); we do not use the term to describe the structure of the reporting system of the firm.

4. Where the academic scientist is working collaboratively on his or her own time, he or she can and does sign any resulting intellectual property rights over to the firm in exchange for mutually agreeable compensation.

5. It is now common practice for universities to require faculty to sign contracts that award rights to all intellectual property they generate in the course of their university duties to the university. However, we are not aware of any lawsuits in which a university has sought to enforce such a contract.

6. One paper on this topic is Kreiner and Schultz (1993) who discuss collaborative networks in biotechnology research in Denmark.

Table 1:
Hierarchical governance of exchanges at Firms X and Y: Numbers of employee-scientists and year of hiring

	Firm X	Firm Y
A. Number of scientists employed by NBF		
Year 10	196	Not available
Year 9	-.-	146
B. Longevity of employment: percentage of scientists who have been with the firm:		
10 years	13.3	not available
9 years	7.7	8.9
8 years	4.6	8.2
7 years	8.7	8.9
6 years	2.6	11.6
5 years	10.7	4.1
4 years	14.3	6.8
3 years	16.3	28.8
2 years	17.4	17.1
1 year	4.6	12.3
5 years or more	47.4	35.0

[a] Scientist-employees are classified as all individuals whom the two firms identified as being "scientists" in their corporate records. Most of these individuals had PhD's or other higher education qualificiations in relevant disciplines such as microbiology and biochemistry.

Source: Corporate records.

Table 2:
Inter-organizational market and quasi-market arrangements for sourcing scientific knowledge at firms X and Y

		Type of Institution involved				
		Universities		Firms		
		U.S.	Int'l.	U.S.	Int'l.	Total
A. *All market arrangements* [a]						
Firm X		0	0	15	5	20
Firm Y		2	2	21	16	41
Total		2	2	36	21	61
B. *Market arrangements for sourcing scientific knowledge:* [b]						
Firm X						
	Number	0	0	2	0	2
	% of total					10
Firm Y	Number	1	1	4	0	6
	% of total					15
Both firms						
	Number	1	1	6	0	8
	% of total					13

[a] Defined as all market and quasi-market organizational arrangements (Williamson , 1991).
[b] Defined as all market and quasi-market arrangements in which the NBF is primarily sourcing scientific knowledge from other organizations. These include five long-term R&D contracts, one R&D-sourcing joint venture, one equity investment in another R&D firm, and one licensing agreement.
Sources: Corporate records, *North Carolina Biotechnology Database, BioScan* , *Wall Street Journal Index*.

Table 3:
Number of scientific collaborations resulting in published research classified by exchange governance mechanism

	Number of Research Publications		
	Firm X	Firm Y	Total
1. Total number of publications	503	345	848
2. Number of publications based on research collaboration with external scientists	257	256	513
Percent of total	51%	74%	60%
Of which are governed by market arrangements that are			
(a) inter-organizational	0	2	0
(b) individual-level	0	0	0
3. Number of publications produced only by scientist-employees	246	89	335
Percentage of total	49	26	40

Table 4:
Frequency of collaboration in published research between scientists at Firms X and Y and external scientists by type of institution of affiliation of external scientists

	Type of Institution				
	Universities and other nonprofit research institutions		Firms		
	U.S.	Int'l.	U.S.	Int'l.	Total
A. *Number of institutions:*					
Both firms					
Number	157	93	28	13	291
% of total	54	32	10	4	100
Firm X					
Number	85	36	17	6	144
% of total	59	25	12	4	100
Firm Y					
Number:	72	57	11	7	147
% of total:	49	39	8	4	100
B. *Mean number of collaborations per institution by type:*					
Both firms	3.28	2.05	1.53	1.08	
Firm X	3.31	2.08	1.88	1.16	
Firm Y	3.25	2.03	1.18	1.00	

Sources: Corporate records of Firms X and Y, journal references.

Table 5:
Number of external research collaborations at Firms X and Y by institution (all years combined)

Number of Publications per Institutional Collaboration	Number of Collaborations by Institution and by Frequency Category		
	Firm X	Firm Y	Total
1-5	130	134	264
6-10	9	7	17
11-15	2	3	5
16-20	1	0	1
21-25	1	1	2
26-30	1	0	1
31 +	0	1	1
Total	144	147	291

Table 6:
Number and rate of external collaboration at Firms X and Y by year

	Firm X			Firm Y		
		Proportion of Publications per Year Involving:			Proportion of Publications per Year Involving:	
Year	Total Number of Publications per Year	External Scientists	No External Scientists	Total Number of Publications per Year	External Scientists	No External Scientists
1	0			0		
2	0			0		
3	18	.22	.78	13	.77	.23
4	39	.23	.77	21	.81	.19
5	56	.45	.55	50	.86	.14
6	56	.32	.68	56	.77	.23
7	82	.60	.40	47	.66	.34
8	73	.58	.42	56	.68	.32
9	82	.59	.41	60	.75	.25
10	107	.58	.42	42[a]	.80[a]	.20[a]
Total:	503	.50	.50	345	.74	.26

Table 7:
Exclusive versus shared patent rights of Firms X and Y

	Firm X	Firm Y
Total number of patents[a]	28	21
Number of exclusive patents	25	19
Number of shared patents	3	2
Number of patents shared by NBF with institutions, or scientists at institutions, with which NBF has a formal contractual agreement	3	2
Number of patents shared by NBF with institutions, or scientists at institutions, with whose scientists NBF scientists have collaborated in published research	0	2

[a] Defined as major patents in force at the time of writing; numbers do not include patents applied for and not received and do not include separate claims made under each patent.

Sources: Corporate records, patent records.

Figure 1:
Hierarchies as support for both markets and social networks in the external exchanges of an NBF