Networks, Propinquity, and Innovation in Knowledge-intensive Industries

Kjersten Bunker Whittington
Reed College
Jason Owen-Smith
University of Michigan
Walter W. Powell
Stanford University
Santa Fe Institute

Industrial districts and regional clusters depend on the networks that arise from reciprocal linkages among co-located organizations, while physical proximity among firms can alter the nature of information and resource flows through networks. We consider the joint effects of geographic propinquity and network position on organizational innovation using negative binomial count models of patenting activity for U.S.-based life science firms in industrial districts and regional clusters across a 12-year time period, 1988–1999. We find evidence that regional agglomeration and network centrality exert complementary, but contingent, influences on organizational innovation. Results show that in the high-velocity, research-intensive field of biotechnology, geographic and network positions have both independent and contingent effects on organizational innovation. The influence of centrality in local, physically co-located partner networks depends on the extent to which firms are also embedded in a global network comprising physically distant partners. Such global centrality, however, alters how proximity to two important classes of organization—other biotechnology firms and public sector research organizations, such as universities, research institutes, and teaching hospitals—influences innovation. Regional agglomeration shapes the character of information and resource flows through networks, while much of what makes industrial clusters region-like involves the structure of their internal networks. We conclude that network effects persist both independently and interdependently with geographic variables, and regional characteristics influence the degree to which centrality enhances innovation.●

Current explanations for scientific and technical discovery in industry emphasize two distinct conceptions of location. Economic sociology rests on the argument that on-going relationships generate and sustain markets. Positions in networks shape access to the information and resources that support innovation (White, 1981; Burt, 1992; Podolny, 2001). In contrast, economic geography stresses the importance of regional industrial agglomeration, making physical propinquity the wellspring of scale and information benefits that enhance the productivity of co-located firms (Krugman, 1991; Jaffe, Trajtenberg, and Henderson, 1993; Arthur, 1994). Numerous studies suggest that networks are crucial to understanding the dynamics of industrial clusters (Saxenian, 1994; Sorenson and Audia, 2000; Sorenson and Stuart, 2001). In turn, analyses of information spillovers point out that local knowledge flows often stem from alliances among organizations, as well as the social connections that link employees of disparate companies (Almeida and Kogut, 1999; Singh, 2005). Scant research, however, has explicitly considered the interplay of regional and relational conceptions of position. Organizations are situated in both geographic and social structural spaces. Both types of locations matter, yet we know little about how they mutually determine organizational outcomes.

Trade and industries frequently cluster geographically (Porter, 2000a; Fujita and Krugman, 2004). Such agglomeration can

0001-8392/09/5401-0090/$3.00.

●

Research and fellowship support was provided by grants from the National Science Foundation (#0097970 and #0545634), the National Bureau of Economic Research, and the Hewlett Foundation through a grant to the Santa Fe Institute. We thank the members of the Powell "lab" group, the Scancor Seminar, the Co-Evolution of States and Markets group at SFI, and the Harvard Business School Entrepreneurship Conference for helpful comments on earlier drafts. Thanks also to Tim Bresnahan, Dan Carpenter, Elisabeth Clemens, Lee Fleming, Mauro Guillén, Bruce Kogut, Paul McLean, John Padgett, Charles Perrow, Annalee Saxenian, Olav Sorenson, Josh Whitford, and Marc Schneiberg for very useful suggestions. We are very grateful to Elaine Romanelli and three anonymous *ASQ* reviewers for rich, constructive feedback. All remaining errors are, of course, our own.

range from the crowding of shops and services in urban neighborhoods to the characteristic core-periphery structure of world trade (Alderson and Beckfield, 2004; Glaeser, 2005). At an intermediate level of analysis, a thriving literature links co-location to economic and organizational outcomes, with particular attention to innovation in technology-intensive regions such as Silicon Valley (Feldman and Florida, 1994; Bresnahan and Gambardella, 2004; Romanelli and Khessina, 2005). Economic geographers have examined the benefits of agglomeration that accrue when co-located firms and diverse sets of complementary organizations mingle with existing labor and supply markets in regional centers. Foundational works in this tradition have explored the mechanisms by which geographically clustered organizations benefit from their locations (Marshall, 1920; Perroux, 1950; Jacobs, 1961; Jaffe, 1986). They have identified the reduced costs of moving goods, people, and ideas as the primary sources of advantage from industrial agglomeration (Asheim, 2000; Porter, 2000b). Where external economies of scale allow clustered firms to benefit from collective resources, local spillovers make their research and development programs more fertile than those of their isolated competitors (Audretsch and Feldman, 1996; Agrawal and Cockburn, 2002).

Social network analysts have focused attention on the abstract contours of a social space comprising concrete relationships among entities. Whether because of gaps in a web of relationships (Burt, 1992), indirect ties connecting partners (Ahuja, 2000), or central locations in an industry structure (Walker, Kogut, and Shan, 1997; Stuart, 2000), networks can dictate access to information and resources, thus enhancing performance. The social network tradition has largely ignored physical space, yet the idea that place is important to understanding innovation has wide credence. Moreover, evidence that shows proximity's effects on network tie formation is mounting (Powell et al., 2005; Sorenson, 2005; Sorenson and Stuart, 2008). Integrating these two perspectives holds promise for understanding how propinquity and centrality might jointly and individually influence innovation.

Combining geography and social structure integrates arguments that appear, at first glance, to be contradictory. Social capital may help distinguish among individual competitors (Burt, 2004), but it also conveys advantage to nations and communities (Putnam, 1993; Portes, 1998). Similarly, the positive effects that regional agglomeration exerts on corporate performance can mask possible negative outcomes that stem from overcrowding in densely connected, fast-moving industries (Stuart and Sorenson, 2003; Sorenson and Waguespack, 2006). The rising tide of spillovers and positive benefits may float many boats in a thriving regional cluster, but competition within regions is often much more intense than outside them. Moreover, though many locales are home to similar institutional resources, successful high-technology clusters are relatively rare (Almeida and Kogut, 1999; Casper, 2007). Opportunities and constraints are unevenly distributed both within and across geographic agglomerations, and the extent to which proximity benefits all participants may well depend on the network structure of a region.

Moreover, Malmberg and Maskell (2006) and Bathelt, Malmberg, and Maskell (2004) have suggested that there are qualitative differences between local and global networks and their modes of interaction. Information and exchange within a local environment generates "buzz," news that is fresh and validated through observability and comparability. More distant exchanges vary, as partners have to be located and choices made about how much information to share and how to monitor long-range activities (Nicholas, 2009; Bengtsson and Ravid, 2009). Formal relationships that span distance offer clear examples of the pipelines that are key to contemporary network theory (Owen-Smith and Powell, 2004). Thus the effects that networks exert on organizations must be considered in light of the physical proximity of partners. We examine the contingent effects that network centrality and geographic propinquity exert on innovation by human therapeutic and diagnostic biotechnology firms. Our research bridges the gap between approaches that take physical location to be a key source of advantage for knowledge-intensive firms and those that link differential rewards to salutary positions in social networks.

SPACE, STRUCTURE, AND INNOVATION IN INDUSTRY

Geographic Effects: Scale and Spillovers

Physical agglomerations of organizations in the same (or overlapping) industries generate benefits for co-located firms because these clusters create economies of scale in services such as transportation and specialized labor. The local scale economies that characterize regional clusters allow proximate firms to economize on costs, a dynamic that increases their ability to compete successfully with more geographically isolated rivals. Similarly, the locales that are home to knowledge-intensive industries also speed the pace of innovation as information and skills developed within organizations spill over to those nearby. Knowledge flows across organizational boundaries in all industries, but the intensity and effects of such streams are heightened by spatial proximity (Jaffe, 1989; Gertler, 1995; Maskell and Malmberg, 1999).

In knowledge-intensive industries, the returns from scale in areas such as transportation seem unlikely to influence firm-level innovative capacities. But the deep, specialized technical labor pools that sustain regional concentrations of similar employers enable the research and development programs of co-located firms to be more fruitful (Saxenian, 1994). Proximity to other firms in the same industry is likely to increase innovation through three closely related mechanisms. First, robust local scientific labor pools will make it easier for firms to locate and recruit the researchers that underpin successful innovation efforts (Audretsch and Stephan, 1996). Second, greater concentrations of scientists are likely to be accompanied by social connections that bridge researchers who share membership in "invisible colleges" or "communities of practice" (Crane, 1978; Brown and Duguid, 1991). Interpersonal networks that span the boundaries of organizations are potentially important channels for the information spillovers that can accelerate innovation in knowledge-based industries, particularly regional clusters. Third, while social networks among scientists facilitate information flows among firms, labor market mobility also has positive effects on innovation. The interfirm mobility of engineers and scientists is a key source of advantage for regions (Casper, 2007; Fleming, King, and Juda, 2007) as well as companies (Almeida and Kogut, 1999; Song, Almeida, and Wu, 2003). Learning through hiring is an important source of spillovers and a correlate of increasing innovation. Because all three of these mechanisms (access to human capital, social-network-based spillovers, and learning by hiring) lead us to expect that physical proximity to similar firms will increase a company's ability to innovate, we make no effort to disentangle them.

Hypothesis 1: In knowledge-intensive industries, firm-level innovation increases with proximity to other companies in the same industry.

Other firms in the same industry are not the only sources of scale and spillover effects in research-intensive industries, however. Venture capital firms, along with specialized law firms, act as sources of managerial and financial expertise, and both are important matchmaker organizations (Suchman, 1995; Powell et al., 2002; Patton and Kenney, 2005). Public research organizations (PROs)—including universities, research institutes, and teaching hospitals—are vital sources of innovation because they are the producers of both technical personnel and cutting-edge scientific knowledge. Universities, in particular, are key sources of human capital in the form of both star scientists and technical employees (Kenney, 1988; Zucker and Darby, 1996; Murray, 2002).

In addition, science has a strong craft element, and having a hand in the discovery process provides a unique initial advantage to replication. Not surprisingly, these tacit insights are more often shared by members of an agglomerated area, especially during early use of a method or tool when knowledge has yet to enter the wider corpus of science (Henderson, Jaffe, and Trajtenberg, 1998; Adams, 2005). These benefits are further amplified by the fact that public research organizations operate largely according to the norms of open science, thus the research discoveries and techniques they make are more accessible than those made by firms (Owen-Smith and Powell, 2004; Sorenson and Fleming, 2004). In research-intensive industries, the presence of public research organizations in a region should increase information flows and further accelerate innovation by nearby firms, even when there are few other corporations in the same location. As with proximity to similar firms, co-location with public research organizations should increase firm-level innovation by enhancing access to scientists and discoveries.

Hypothesis 2: In knowledge-intensive industries, firm-level innovation increases with proximity to public-sector research organizations.

Interorganizational Networks: Global and Local Centrality

Despite the importance of propinquity, some successful organizations lack neighbors, while even companies located in robust regional clusters commonly forge connections that reach beyond their immediate locales. So it comes as no surprise that sociological studies of innovation have demonstrated the importance of centrality in geographically dispersed networks. Whether conceptualized in terms of social connections among individuals (Granovetter, 1973; Uzzi, 1996), informal affiliations among corporations (Mizruchi, 1992; Davis, Yoo, and Baker, 2003), or contractual alliances that formally link organizations (Eisenhardt and Schoonhoven, 1996; Powell, Koput, and Smith-Doerr, 1996), networks have been shown to play a key role in shaping both knowledge flows and the structure of industries. Networks aid organizations by serving both as pipelines that channel flows of resources among positions in a social structure and prisms that provide insight into which participants are reliable (Podolny, 2001). As a result, organizations tend to perform better when they are centrally positioned in industry networks. Firms that have more cohesive and extensive networks have been shown to have lower failure rates (Uzzi, 1996) and greater success on a variety of outcome measures (Mizruchi, 1992; Stuart, Hoang, and Hybels, 1999; Ingram and Roberts, 2000).

Similarly, a wealth of research documents a strong correlation between an organization's network of partnerships and its innovative output, particularly in research-intensive industries, in which networks serve as the locus of innovation (Powell, Koput, and Smith-Doerr, 1996). Hagedoorn and Schakenraad (1994) have shown a positive relationship between the frequency of technological partnerships and rates of innovation in a number of high-tech sectors, while others have demonstrated that strategic alliance networks increase innovation rates in biotechnology (Shan, Walker, and Kogut, 1994; Walker, Kogut, and Shan, 1997). Stuart (2000) found parallel effects in the semiconductor industry but observed that returns to innovation depend on partners' characteristics. Similarly, Ahuja (2000) reported that strategic alliances have beneficial effects on patenting in the international chemical industry.

An organization's networks play a particularly important role in geographically concentrated industries because the likelihood and effects of ties are often constrained by distance. Thus local and global network structures may exert different effects on innovation that should be distinguished from each other. A firm's global position refers to its location in an industry-wide network of collaborative relations and contractual ties, irrespective of partners' geographic locales. In agglomerated areas, an active local network connects those who share both a physical and structural space.

Global centrality. Networks can enable firms to access quality information across gulfs of physical space. Distance makes scientific and technological collaboration more difficult and necessitates more formal coordination and control efforts (Olson and Olson, 2000). Although alliances that connect far-flung partners may involve fewer social affiliations than those that connect co-located partners, more formal, proprietary efforts at managing and monitoring collaborations make the transfer of complex information across considerable distance possible. Formal interorganizational networks thus offer access to knowledge and resources to companies in regional clusters as well as to those with few neighbors. Even the organizations that benefit from geographic propinquity may see distinct returns to connections with physically dispersed partners. Because globally dispersed linkages may be of variable quality, advantages should be greatest when dispersed connections provide linkages to the most central, well-situated firms in the global network.

The ability to draw high-quality ideas and practices from far-flung yet well-connected sources may allow an organization to bring together this information with that derived from more informal interactions with proximate partners. This offers an additional boost to organizations that are located near others and central in geographically dispersed interorganizational networks. More interestingly, the infusion of ideas into dense regional clusters via formal network connections to outside firms may mitigate the possibility that the knowledge base of regional industries might become ossified as social and labor market connections grow inbred. Contractual network ties situate both proximate and distant companies in a global industrial structure. A central position in such a network facilitates innovation. Thus global centrality yields advantages regardless of an organization's physical location because alliances can effectively convey information and resources across distance.

Hypothesis 3: In knowledge-intensive industries, firm-level innovation increases with centrality in the global interorganizational network.

Local centrality. Geographic proximity facilitates the formation of interorganizational ties, and these local alliances enhance the effects that propinquity exerts on firm performance (Almeida and Kogut, 1999). Regional economies, industrial districts, or clusters are characterized by overlapping personal, organizational, and professional networks. Indeed, Kogut (2000) and Brown and Duguid (2000) have both argued that in densely clustered regions, networks of social relations are the primary source of new knowledge for co-located firms. The effects that physical location exerts on performance, however, are most commonly examined separately from analyses of network structure.

Although far-flung networks influence innovation, recent work suggests that geographic proximity may alter the ways in which organizations take advantage of their connections. Even though crowded regional clusters may not be ideal locations for new entrants, the geographic stickiness of social networks can compel founders to locate new ventures close to established incumbents (Sorenson, 2005). At the individual level, Singh (2005) demonstrated that the distribution of ties among inventors may explain how knowledge is restricted within regional boundaries. Fleming and Marx (2006) showed that inventors in Silicon Valley are linked through graduate school experience, participation in post-doctoral programs at corporate research labs, and common employment histories. This work suggests that organizational outcomes and individual networks are mutually constitutive.

In regions where fluid labor markets, porous organizational boundaries, and significant interactions with academe bolster information disclosure, alliances between organizations generate additional social and business connections that amplify information flows among collaborators. Formal interorganizational alliances among nearby partners may promote greater, more rapid, or more regular exchanges of knowledge and resources than proximity alone. Thus a central location in the alliance network internal to a cluster, what we term the local network, is likely to differentiate among physically agglomerated organizations by exerting an independent influence on their capacity to innovate. Centrality in local networks is consequential to the extent that it expands access to resources and information above and beyond what is available through the personal networks of employees or what can be secured through judicious hiring. Though all firms in a region may gain from agglomeration effects, those that are central participants in local networks should garner the greatest returns.

Hypothesis 4: In knowledge-intensive industries, firm-level innovation increases with centrality in local interorganizational networks.

Because organizations in research-intensive industries situate themselves in both physical and social structural spaces, it is possible that proximity (to other firms and to public-sector research organizations) and centrality (in local and global interorganizational networks) will exert joint and/or contingent influences on scientific and technological innovation.

Contingent Effects: Propinquity and Centrality

For firms with few or no geographic neighbors, the probability of local interorganizational network ties is low, but firms that are physically located in regional clusters can forge alliances with partners both distant and nearby. For these firms, global and local partnerships will influence innovation in subtly, but importantly different fashions. Both forms of collaboration are formal, but global connections between distant partners depend largely on contractual assurances and prescheduled visits and exchanges to enable information flow. Hence, the kinds of technical, often very tacit information that is essential to the R&D process is less easily transferred between distant partners. In contrast, local interorganizational collaborations are forged and maintained in a regional cluster that is rife with various informal social channels for information transmission. In local networks, then, information should spill over among firms, even when formal means are invoked to limit or direct its transfer (Powell, 1990; Chesbrough, 2003). More importantly, formal connections often overlap considerably within social channels to speed information flow within regional clusters.

There are two reasons why the diverse character of these two types of connections may reveal contingencies when separately maximized in research-intensive industries. First, geographically proximate connections exist in a context that enforces reputational consequences and the possibility of long-term partnerships. The presence of established norms of cooperation influences governance mechanisms and the ability of others to observe and sanction poor partnership behavior. Local connections are strengthened by the social context surrounding them, and increasing centrality in the local network may reduce the influence of global connectivity.

Second, the challenge of global partnerships is to create alliance pipelines that are both sufficiently tight and reliable enough to successfully transfer information in the absence of dense social connections. In contrast, the trick of local interorganizational networks is to keep formal connections loose enough to avoid shutting out the potentially useful information that arrives via more diffuse social channels (Owen-Smith and Powell, 2004; Singh, 2005). Although this distinction is unlikely to be hard and fast—because people maintain active social connections that cross the boundaries of physically distant organizations—the logics and competencies required to capitalize on central positions in both local and global interorganizational networks can be at cross purposes. This juggling act may be particularly salient when interactions among the members of a regional industry foster norms of openness and participation that undermine the formal mechanisms for controlling and directing information flow that are necessary to efficacious global ties.

Thus organizations with finite capacities to develop, maintain, and exploit network ties may face tradeoffs in managing tight, formally governed, and geographically dispersed collaborations, while also maintaining their positions in local networks. These effects will be stronger to the extent that the rich social context that surrounds and supports local alliances reduces the organizational costs of managing and monitoring proximate relationships. If local ties provide more effective means to access information similar to that which can be found at a physical distance, then a greater reliance on local ties will further diminish the importance of global connections.

Hypothesis 5: In knowledge-intensive industries, increasing local centrality will decrease the effect of global centrality on innovation at the firm level.

At the heart of discussions concerning proximity and networks is the question of whether these two conceptions of distance represent separate, contingent, or complementary spurs to innovation, and there are competing logics that can be used to assess the joint impact of networks and propinquity. The returns that accrue to proximity with other industry firms, for instance, may be sufficient to reduce firms' need to maintain connections to geographically dispersed partners, or vice versa. Hence, firms located at a considerable distance from other key organizations may see greater payoffs from increasing their global connections than those with many geographic neighbors. In this view, global networks may work to alleviate the challenges of physical distance and thus substitute for the benefits of proximity.

In contrast, formal alliances and informal spillovers may convey different types of information at different speeds and with varying degrees of accuracy. Proximity to other firms or to public research organizations might increase innovation, completely independent of centrality in global networks. If this is the case, then a firm's networks operate more or less in isolation from its physical location. Here, geographic and structural positions will independently influence outcomes via separate mechanisms. Finally, the effects of propinquity and centrality may be complementary. In this scenario, the information and capacities gained through global networks will enhance a firm's ability to benefit from proximity, and vice versa. If networks and proximity work in tandem to enhance innovation, then those organizations that lack access to both far-flung connections and large numbers of neighbors will be uniquely disadvantaged, while firms that are both proximate and central will be the most innovative. The current literature provides little guidance as to which outcome to expect. Hence we choose to treat this relationship as an empirical problem and test for all three options:

Hypothesis 6: In knowledge-intensive industries, proximity to other firms in the same industry and to public research organizations and centrality in a global interorganizational network may be (a) independent, exerting no contingent effects on innovation; (b) substitutes, such that increasing one dampens the effect of the other; or (c) complementary, such that increasing one amplifies the effect of the other.

If the first condition holds, then the effect of geographic and structural positions on innovation is independent and additive. If the second possibility is supported, then firms would be best served by maximizing either their physical proximity to other companies and public research organizations or their centrality in the global network, but not both. Finally, if the last condition proves true, and proximity and centrality exert complementary effects, then the most efficacious stance would match physical locations near other firms and public research organizations with centrality in global networks. In the latter case, it seems likely that organizations that are not located in regional clusters or that are proximate but peripheral to the global network are at a distinct competitive disadvantage relative to companies that benefit from both centrality and propinquity.

METHOD

The Setting: Contemporary Biotechnology

The commercial field of biotechnology emerged from discoveries in university labs in the 1970s, witnessed the founding of hundreds of small science-based organizations in the 1980s, and matured in the 1990s with the release of numerous new medicines. This field combines scientific, organizational, and commercial advances made by a diverse cast of organizations, including universities, public research institutes, large multinational pharmaceutical corporations, and smaller dedicated biotech organizations, as well as venture capital firms, law firms, and university technology transfer offices. Because the sources of life-science research leadership were widely dispersed and developed rapidly, while the relevant skills and resources needed to produce new medicines were very broadly distributed, the participants in the field found it necessary to collaborate with one another (Orsenigo, 1989; Gambardella, 1995; Powell, Koput, and Smith-Doerr, 1996). Concomitant with changes in the density of the industry network, an elaborate system of private governance evolved to orchestrate and harmonize the thicket of interorganizational relationships (Powell, 1996). Over time, the internal structure of many organizations changed, co-evolving with transformations in the patterns of affiliation that characterized the industry network (Galambos and Sturchio, 1996; Powell et al., 2005). As in other high-technology sectors, interorganizational networks are an essential component of the biotechnology business model (Hagedoorn and Roijakkers, 2002). Some recent commentators, however, have contended that scientific advance has come at the expense of business success (Pisano, 2006).

Biotechnology is a useful case study for this analysis because there is ample evidence that both proximity and network relationships play an important role in the innovation process. Early discoveries by a handful of star academic scientists led to their subsequent involvement with start-ups located close to their home universities (Zucker and Darby, 1996; Zucker, Darby, and Brewer, 1998). The regional labor market for scientists, in turn, benefited from agglomeration effects as these technologically active areas attracted deeper pools of industry-specific talent, and scientists moved among firms and between academic and industrial employment within regions (Audretsch and Stephan, 1996; Breznitz and Anderson, 2006). Companies became linked through licensing arrangements with universities, and connections were deepened through faculty memberships on scientific advisory boards and boards of directors, research partnerships, and all manner of interorganizational affiliations (Powell, 1996; Murray, 2002; K. Porter, 2004). As a result, a handful of prosperous biotech regions came to be characterized by large populations of firms, active public research organizations, and local networks of interorganizational alliances. The global interorganizational network that presently characterizes the industry had its genesis in these local affiliations (Owen-Smith et al., 2002).

The spatial concentration of biotechnology is notable. In the U.S., substantial firm agglomeration has occurred in three regions: the San Francisco Bay Area (including Berkeley, Oakland, and Santa Clara County), Boston (including Cambridge), and San Diego. Each area has a strong set of supporting institutions that complement and support commercial development. Although these areas represent the three primary locations in which regional biotechnology clusters have thrived, there are also several nascent clusters, most notably Raleigh-Durham, NC, Seattle, WA, Bethesda, MD, Philadelphia, PA, and the greater New York City metropolitan area (Romanelli and Feldman, 2006).

We focus on firms in all locations to test for key contingencies between networks and proximity and then turn to the three established regions to present complementary models with a further emphasis on the effects of local versus global centrality. Because the three clusters have reached critical mass, we could obtain data on organizations that collaborate with biotech firms in these regions. For other areas of the country, data on exact locations of headquarters of the partner organizations in our dataset are not readily available for all the years in our sample. Although several smaller regions are emerging, our focus on the three dominant regions is driven by considerable past research that supports the primacy and uniqueness of these established clusters. For example, unlike the three larger regions, none of the nascent clusters have the combination of multiple public research organizations, active venture capital investors, and a coterie of established organizations that have successfully developed and marketed new medicines and collaborated with one another. And in biotechnology, both the density of dedicated biotechnology firms and the organizational diversity of partners are critical components of robust regional clusters. Public-sector research organizations contribute stability to regional networks and add openness to information flows. Active venture capital investors accelerate rates of founding, help maintain the industrial density of regions, and provide an alternate channel for information flow. The three established regions are notable for both "enhanced information sharing" as well as a second (and even third) wave of company foundings (Romanelli and Feldman, 2006).

Given our focus on firms in the three established regions, it is important to take into account how firms in these regions differ from those in other areas. First, the impact of the three clusters is evident when one considers the cumulative accomplishments of companies located there. Of the 37 medicines developed by dedicated biotechnology firms and approved by the U.S. Food and Drug Administration's (FDA's) Center for Biologics Evaluation and Research (CBER) from the early 1990s through December 31, 2003, 21 came from companies in these three regions. Six companies were responsible for developing the ten most widely sold biotech medicines in 2001; five of these came from one of the three regions. In our sample, 60 percent of the biotechnology patents and half of the formal contractual collaborations during the 1988–99 time period involve a company in one of these three established clusters.

This is not to say, however, that the firms located in these regions are universally successful. One of the early bellwether firms of the industry, Cetus—located in Emeryville, CA, next door to Berkeley—had a high-profile rejection of its lead drug by the U.S. Food and Drug Administration in 1991 and was carved up between pharmaceutical giant Roche and a then-smaller neighbor, Chiron. More recently, one of the oldest firms in the industry, Alza, which was acquired by Johnson and Johnson in 1994, was closed down in the course of corporate retrenchments. Our data show that failure rates inside and outside of the three regions show no statistical difference except for the San Diego region, in which firms are more likely to fail a bit sooner than those in any other locale ($p > .10$). In addition, there is no significant difference between the percentage of public firms, or the extent of collaborative experience, inside and outside of the three regions ($p > .10$). Although the regions are notable aggregate producers of innovation, they are also challenging arenas, and firms located within regional boundaries face similar competitive demands as firms located elsewhere.

Most importantly, with the exception of the Bay Area, there is no statistical difference between the average yearly patenting rate of firms in the three regions and those outside of them

($p > .10$). And although Bay Area firms have a higher average rate, this region also has a significantly higher standard deviation among its firms. The increased rate is largely due to the patenting activity of two notable firms in the Bay Area, Chiron and Genentech. In other words, mere location in these regions does not appear to increase innovation rates across the board. The variation that we observe among geographically concentrated firms speaks directly to one of the puzzles that make the relationship between proximity and networks such a compelling subject of study.

Data

We drew our sample from an independent industry directory, *BioScan*, founded in 1988 and published six times a year, which covers a wide range of organizations in the life sciences field. Our database comes from *BioScan's* April issue, in which new information is added for each calendar year. Hence all firm-level and network data were measured during the first months of each year. We supplemented Bioscan data with information from U.S. Securities and Exchange Commission filings, Recombinant Capital, the Windhover Alliance database, and Web searches. We focused on dedicated biotech firms (DBFs), defined as independently operated, profit-seeking entities involved in human therapeutic and diagnostic applications of biotechnology. We omitted companies involved in veterinary or agricultural biotech, which draw on different scientific capabilities and operate under different regulatory regimes. For these analyses, we focused only on U.S. firms, although the larger database includes firms from around the globe. The sample of DBFs covers both privately held and publicly traded organizations. The latter include companies that have minority or majority investors, as long as their stock continues to be independently traded. We excluded wholly owned subsidiaries. Large pharmaceutical corporations, healthcare companies, hospitals, universities, or research institutes enter our database as partners that collaborate with DBFs.

The primary sample covers 371 DBFs headquartered in the United States over the 12-year period 1988–1999. In 1988, 205 firms met our sample criteria. During the next 12 years, 166 organizations were founded and entered the database; 86 (of the 371) exited, due to failure, departure from the industry, or merger. The maximum number of firms active in a single year is 297 (in 1997), and 141 firms exist across all years.

The outcome of interest is a yearly count of patents assigned to the DBFs, categorized by application date rather than issue date, as this date best reflects the time when the research was completed (Jaffe and Trajtenberg, 2002). Patents are a commonly used measure of the innovative intensity of firms and industries (Jaffe, 1989; Ahuja, 2000; Stuart, 2000). A U.S. patent offers inventors the legal ability to exclude others from using the protected innovation for a period of 20 years. In an industry characterized by intensive innovation races and a demanding, protracted federal regulatory process, patents convey important strategic advantages and are an especially important means of protecting intellectual property in the bio-pharmaceutical field (Cohen, Nelson, and Walsh, 2000; Coriat and Orsi, 2002; Bulut and Moschini, 2006).

Despite their importance, however, patents are an imperfect measure of innovation. Not all innovations are patented. For instance, firms may use trade secret protection instead of patents on key process innovations, while other types of discoveries, particularly pertaining to social and organizational arrangements, rarely receive formal protection (see Rhoten and Powell, 2007). More importantly, patents can be used strategically in a manner that weakens their innovative value. Some firms practice defensive patenting, through which they seek to maximize the number of overlapping patents they hold in a particular area, to make entering a field difficult for competitors. Under this strategy, individual patents offer limited value and represent at best incremental innovations. Such an approach is less common in the bio-pharmaceutical field than in telecommunications, where a single product may be based on hundreds or thousands of patents. Finally, any issued patent is the outcome of a complex process involving many participants. Inventors, lawyers, and patent examiners may each add their own stamps to intellectual property (Myers, 1995). As a result, successful patenting can reflect an organization's political and regulatory savvy, as well as its scientific prowess. Nonetheless, the salience of intellectual property in the biotechnology industry, the close relation between a specific discovery and a small number of patents or a single patent, and the advantages of longitudinal data that are comparable across multiple organizations combine to make patents a reasonable proxy for innovative capacity in this field.

We matched firm-level and network data from *Bioscan* and other sources with yearly patent counts extracted from the United States Patent and Trademark Office database. Nearly 7,300 (N = 7,299) patents were issued to the 371 firms between 1988 and 1999, with a mean yearly volume of 2.4 patents per firm and a standard deviation of 8.2. Patent counts are known for being highly right-skewed, with only a handful of firms garnering the highest patent counts per year. Though the average per year is 2.4, the median number of patents for the DBFs in our sample is 0.0 per year. All statistical inferences in this research take this overdispersion into account.

Firms from the three largest regions make up 49 percent of the U.S. population and 40 percent of our full international database. The San Francisco Bay Area has the largest percentage of firms (21 percent), followed by Boston (15 percent) and San Diego (13 percent). We conducted the second part of our analysis with a focus on the three established regions, which may raise concerns that we selected on our dependent variable, firm patenting. Our central claims about proximity in this paper, however, derive from models that include all firms in the industry and include no measure of local ties. Hypotheses 4 and 5 incorporate models that underpin the regional sample. Though they include no firms located outside the three focal regions, they also do not artificially truncate our dependent variable, which contains significant variation despite a higher patenting average than firms outside of established regions.

Defining Structure and Propinquity

Proximity to other firms. To test the benefits of being located near other DBFs, we operationalized $proximity_f$ as a continuous, yearly firm-level measure of geographic distance. We used Sorenson and Audia's (2000) localized geographic density measure, which calculates the average distance from a focal firm to every other alter firm in each year in the database. We used the following equation for firm i at time t:

$$LD_{it} = \sum_j \frac{x_j}{\left(1 + d_{ij}\right)},$$

where *x* is the weighting variable (set to one for this analysis), *j* indexes all firms except for firm *i*, and d_{ij} is the distance between firm *i* and firm *j*. This measure increases in magnitude as a firm's proximity to other companies in the industry increases.

We coded regional location for each company in our sample using the postal zip code of the firm's headquarters and found the latitude and longitude for the center of the zip code area using data available from the United States Postal Service. Following Sorenson and Audia (2000), we used the latitude and longitude and spherical geometry to calculate the distance in miles (on a curved surface) between each DBF-DBF pair. The distance between two points, *i* and *j*, can be calculated by:

$$d_{ij} = C\Big\{\arccos\Big[\sin(lat_i)\sin(lat_j) + \cos(lat_i)\cos(lat_j)\cos(|long_i - long_j|)\Big]\Big\},$$

where latitude (*lat*) and longitude (*long*) are measured in radians and C = 3,437, which converts the result to miles on the surface of the earth. We present normalized proximity statistics to account for the changing number of firms per year.

Proximity to PROs. Research universities and public research institutes (PROs) are primary contributors to open science. Thus, to assess the influence of closeness to public science knowledge sources, we operationalized $proximity_p$ as a continuous, firm-level measure of geographic proximity to universities and research hospitals and institutes. We again used the above equations to compute local density, this time calculating the distance from a focal firm and all public research organizations in the biotechnology industry. This measure captures closeness to potential sources of knowledge spillovers, and its value decreases as the distance between a focal firm and a public research organization grows. Because none of the public research organizations changed locations during our time period, we present non-normalized measures.[1]

Social structure. We assessed the effects of social position by appeal to the network of formal contractual relationships linking DBFs and partner organizations. *BioScan* reports data on the time frame and purpose of interorganizational

1
We conceived of an alternative continuous, firm-level measure to adjudicate between "strong" and "weak" sources of public science, which weights nearness by the cumulative stock of patents held by an organization from 1976 to 1999. This measure proved to be highly collinear with network centrality, precluding tests of hypothesis 6. The independent effect of stock-weighted spillovers, however, was similar in sign and significance to the measure we report.

agreements, and we coded all formal ties by their start date and duration. These collaborations can involve research partnerships, licensing agreements, financial investments, manufacturing or marketing contracts, and complex ties that involve multiple stages of the production process. We defined a tie as any contractual arrangement to exchange, provide, or pool resources between a DBF and one or more partner organizations. Previous research shows that all types of ties are crucial to draw in a variety of organizations and promote industry cohesion (Powell et al., 2005). Thus firm-level network position is most accurately defined by a firm's location amidst all types of partners and ties. A connection, or link, exists whenever a DBF and partner have one or more ties between them. These tie data enabled us to construct a formal network linking DBFs and their partners. In addition to the population of U.S. biotech firms, the global network includes 350 universities and public research organizations, 99 government agencies, 743 venture capital firms, and 511 pharmaceutical, chemical, and healthcare organizations.

Centrality in formal collaboration networks allows organizations access to information and resources that may not otherwise have been shared across distances by other means. We operationalized *network position* with a continuous, firm-level measure of centrality that increases in magnitude as a focal firm connects to partners who are themselves well connected. For this analysis, we incorporated Bonacich's (1987) power centrality measure, in which the strength of a focal firm is recursively defined by the sum of the power of its alters.[2] This measure allowed us to specify the extent to which well-connected companies experience innovation gains from being connected to other highly central alters. Using the tie network of firms and organizations, we constructed two firm-level measures of network position, global centrality and local centrality.

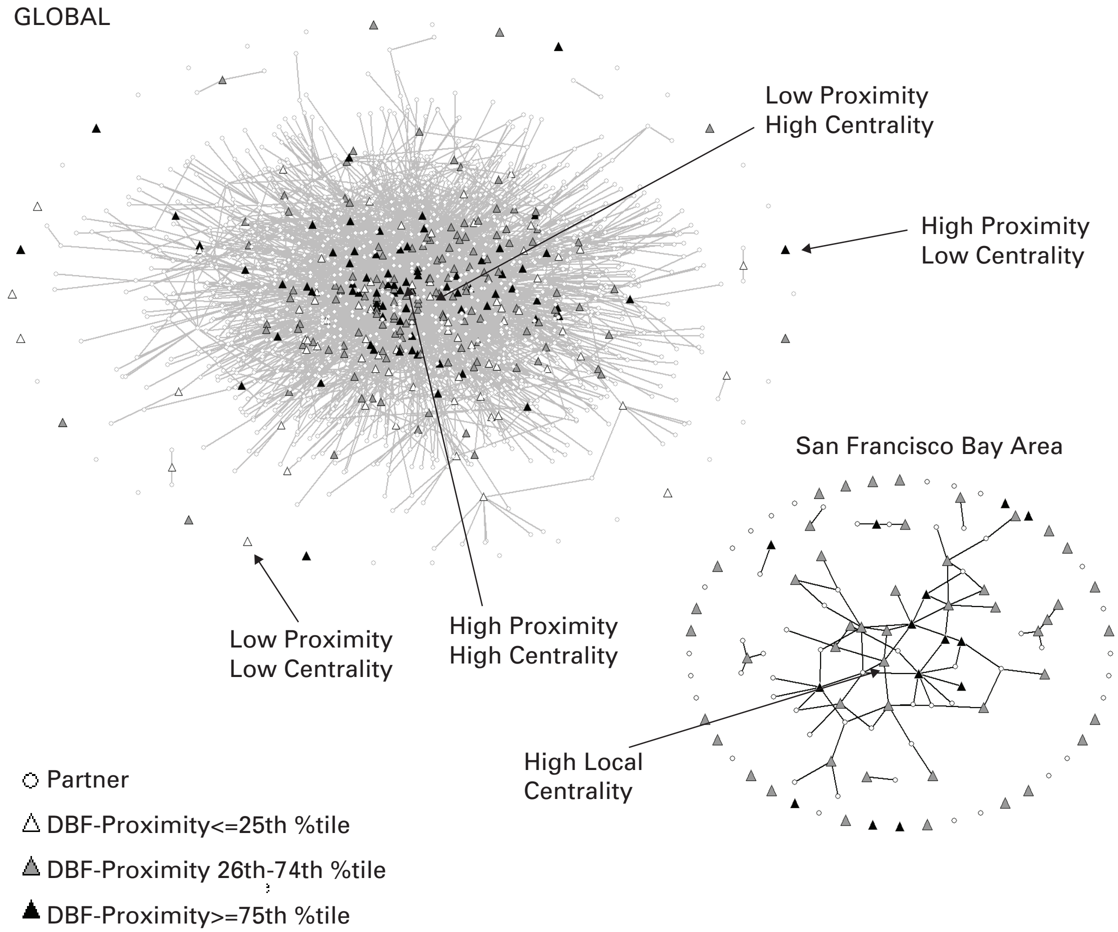
Global centrality. We calculated firm-level power centrality using the full global network of firms and partners, regardless of geographic distance or location. In models that include measures of local centrality, we recalculated global position with all local ties removed in order to gauge the independent effect of local and global connectivity.[3] Across firms, the average network position varies from year to year, but it is somewhat right-skewed, with the highest centrality scores achieved by only a handful of firms. The percentage of companies with non-zero power centrality increases each year, however, ranging from 60 percent in 1988 to 91 percent in 1999. We also included multiplicative interactions between centrality and scale and spillovers. These interactions gauge the extent to which proximity and centrality jointly influence innovation.

Local centrality. We constructed three local networks for the Bay Area, Boston, and San Diego regions, counting only the DBFs and partner organizations physically located in each region and the linkages among them. These networks collectively involve 193 DBFs, 41 public research organizations, one government lab, 99 venture capital firms, and no pharmaceutical, chemical, and healthcare organizations during

2
We found similar substantive results in models run with an alternative centrality measure, Freeman's (1979) measure of betweenness, which considers nodes central to the extent that they sit on indirect connections between other organizations and can thus facilitate, appropriate, or impede information and resource flows in a network.

3
The correlation between global power calculated with and without local ties is .93. Local ties account for approximately 36 percent of the ties for firms in the three regions. Models run using global centrality measures calculated with and without local ties revealed similar signs, significances, and substantive implications as those presented here.

Figure 1. Network position and proximity to other firms, 1999.



this time period.[4] To operationalize local centrality, we again calculated a continuous, firm-level measure of Bonacich's power centrality, this time using only ties in a focal firm's regional network. This measure captures a firm's position in a structure comprising interorganizational ties connecting all partners located in the same region as the focal firm. Local centrality increases in magnitude as a focal firm connects to neighbors who are themselves well connected to other organizations in the region. The measure allowed us to pinpoint the relative effects of global versus local centrality within a regional agglomeration.

Visualizing propinquity and social structure. The presence of regional clusters and the importance of interorganizational networks in this industry allowed us to investigate how social structure and geographical proximity jointly shape innovation. Figure 1 illustrates how we conceptualized these factors, using network data from our sample for the year 1999.

Figure 1 presents two images of interorganizational networks: the larger image on the left represents the global network of organizations involved in biotechnology; the smaller image on the right displays the local network for the San Francisco Bay Area. In both graphics, the DBFs that are the focus of our

4
Only beginning in 2000 did large pharmaceutical companies such as Pfizer and Novartis relocate their R&D centers to Cambridge, MA. Amgen, one of the largest biotech companies and based in Los Angeles, recently acquired a small, well-regarded biotech, Tularik, to create a Bay Area beachhead and has also opened R&D facilities in Cambridge, MA. Merck, Johnson and Johnson, Pfizer, and Novartis have all recently set up R&D facilities in the San Diego area. These recent efforts by large firms reflect their attempt to capture the gains of relational advantage in the regional clusters that we analyze.

analysis appear as triangles. Partner organizations of all types are represented as small, ghosted circles. The grayscale shading of triangles reflects variations in our measure of proximity to other firms. White triangles are most distant from other firms in their industry, black triangles are the most proximate and thus candidates to benefit from the salutary effects of propinquity. Taken together, the two images illustrate the varied ways in which networks and propinquity can interact.

In the global network, the spread of differently shaded triangles across the image suggests that proximity to other firms does not necessarily accompany centrality in a dispersed network. The darkest triangles in this image are spread fairly evenly across the network. Some firms with high proximity scores are also central, while others are clearly peripheral. Similarly, the lightly shaded triangles, representing firms that are geographically distant from others in the industry, also appear at both the center and the margins of the network. Figure 1 suggests that centrality and propinquity overlap imperfectly, a suggestion supported by the correlations reported in table 1 (below), which imply a relatively weak association. Proximity to firms correlates with global centrality at .10, while proximity to PROs correlates even less strongly at .06. Individual firms can therefore be usefully characterized by both proximity to others and centrality in a global network. These different positions should exert distinct influences on innovation in biotechnology.

The smaller image in figure 1 illustrates the important role that networks play within regions. Though all firms in this image have the relatively high proximity scores that one would expect for companies in the Bay Area, variation is nonetheless apparent. But those differences do not translate cleanly into local network positions. Some of the most physically proximate firms in the Bay Area (the black triangles) have no local ties. More important for our argument is the cohesive network component at the center of this image. All the firms in and around San Francisco may gain from their physical location, but not all are equally well positioned in the local network. Even though propinquity alone may afford benefits based on access to regional labor markets, centrality in local interorganizational networks such as the one represented here should convey different innovative advantages.

These visualizations suggest the complex ways in which physical and structural conceptions of location and proximity can overlap and alter one another. Although they are conceptually distinct, physical co-location, as well as regionally bounded and geographically dispersed network structure, represent a variegated topography on which firms can prospect for novelty and pursue innovation. In some cases, centrality in the global network may overcome challenges associated with local isolation. All locales are not created equal, however, and access to the information and resources that flow through a regional network may make the difference between proximity and participation fateful. Hence, the innovative advantages of propinquity and network ties may rely on important contingencies among proximity and local and global networks.

Table 1

Descriptive Statistics and Correlation Matrix of Firm- and Network-level Characteristics for all U.S. firms, 1988–1999 (N = 2,868 firm-years)

Variable	Mean	S.D.	Min.	Max.	1	2	3	4	5	6	7	8
1. Patent count	2.42	8.20	0	188								
2. Publicly held*	.55		0	1	.14							
3. Age (years)	7.42	5.10	< 1	31	.11	.46						
4. Age squared	88.96	111.94	0	961	.11	.35	.94					
5. Collaborative experience (years)	5.77	4.25	0	26	.10	.51	.78	.69				
6. Previous year patent count (logged)	.68	.87	0	5.24	.51	.31	.19	.14	.23			
7. Global centrality	11.92	16.70	0	163	.41	.35	.28	.23	.40	.46		
8. Proximity$_{(firm)}$ (normalized)	.02	.03	0	.10	.02	–.01	–.13	–.12	–.03	.08	.10	
9. Proximity$_{(PRO)}$	1.83	2.02	.12	7.12	–.01	–.01	–.08	–.09	.02	.03	.06	.73

* The reference category for publicly held is privately held.

Table 2

Descriptive Statistics and Correlation Matrices of Firm- and Network-level Characteristics for Firms in the Boston, San Diego, and San Francisco Bay Area, 1988–1999 (N = 1,347 firm-years)

Variable	Mean	S.D.	Min.	Max.	1	2	3	4	5	6	7	8	9
1. Patent count	3.33	11.06	0	188									
2. Publicly held*	.53		0	1	.17								
3. Age (years)	7.42	4.93	< 1	31	.19	.46							
4. Age squared	79.24	106.26	0	961	.21	.34	.94						
5. Collaborative experience (years)	5.43	4.13	0	19	.16	.57	.78	.65					
6. Previous year patent count (logged)	.81	.95	0	5.24	.52	.37	.32	.29	.35				
7. Local centrality	2.03	3.28	0	21	.08	.17	.07	.05	.17	.20			
8. Global centrality (minus local ties)	10.77	13.92	0	117	.45	.37	.39	.36	.48	.52	.38		
9. Proximity$_{(firm)}$ (normalized)	.04	.03	.001	.104	–.07	.02	–.12	–.13	.02	–.04	–.07	.01	
10. Proximity$_{(PRO)}$	2.91	2.41	.32	7.21	–.08	.03	–.07	–.10	.06	–.07	–.09	–.001	.64

* The reference category for publicly held is privately held.

Control variables. Lastly, we incorporated a variety of firm-level controls into our models. We included a yearly dummy variable indicating whether or not a firm was publicly or privately held, and continuous variables indicating firm age, a quadratic term for firm age, the number of years of collaborative experience (measured by the number of years since first tie), and a measure of the firm's patent count in the previous year (logged, by application date).[5] Tables 1 and 2 present descriptive statistics and correlation matrices for all variables used in the analysis. Table 1, which reports measures for the full sample, indicates that the DBFs in our sample tend to be young and almost evenly split across public and private ownership. As might be expected, these firms vary widely in the extent of their collaborative experience and in the size of their patent portfolios. Table 2 presents descriptive statistics

5
We used a measure of past patent behavior to account for experience with the patent process and firm propensity to engage in commercial behavior. We used patent counts for the previous year rather than a cumulative count because year-to-year variation may be associated with firm centrality. In addition, using lagged counts rather than cumulative counts avoids left censoring problems for firms in the first year of our dataset. Results from models run with a cumulative count, however, did not differ substantially in sign or significance, and all interpretative results remain the same.

for firms in the three regions only. Regional firms look remarkably similar to non-regional firms on most measures, with the obvious exception of the proximity measures.

Model Specification

In our first analysis, we modeled counts of patents by application date in an 11-year pooled cross-section for a panel of 371 U.S. DBFs, beginning with 1989 because the database on which we drew began in 1988. The unit of analysis is a firm in a given year, and there are a total of 2,868 firm-year observations in the final sample (on average, 7.7 observations per firm). In our second analysis, we constrained our sample to focus on firms in Boston, San Diego, and the San Francisco Bay Area to ascertain the effects of local network centrality in regional clusters. Again, the unit of analysis is a firm in a given year, and there are 1,347 firm-year observations in the region-only sample (on average, 6.9 observations per firm). We also present the first set of models with indicator variables for the three regions and other, more nascent regions (Raleigh-Durham, NC, Seattle, WA, Bethesda, MD, Philadelphia, PA, and the greater New York City metropolitan area) to show the effects of proximity, controlling for location in notable regional clusters.

All models were estimated with a negative binomial specification to allow for overdispersion of the variance in the dependent variable (Hausman, Hall, and Griliches, 1984; Cameron and Trivedi, 1998; Allison and Waterman, 2002). All models include centered independent continuous variables, as well as yearly fixed effects—dummy variables for each year except one—to control for period effects and unobserved heterogeneity across time.[6] We report all model statistics with robust standard errors (clustered by firm) to account for repeated measurements on sampling units across time.

RESULTS

Table 3 presents the results from a series of fixed-year negative binomial count models. Model 1 presents the regression coefficients from our control variables in this analysis. Models 2–5 demonstrate the direct effects of proximity_f, proximity_p, and global centrality, separately and together. Model 6 includes interactions between global centrality and our two measures of proximity. Across models, the control coefficients remain remarkably consistent in sign, magnitude, and significance. The coefficients indicate that a firm's propensity to engage in patenting behavior in the past and its publicly traded status have particularly strong effects on yearly patent output. Collaborative partnership experience is initially positive but loses its significant effect in later models, suggesting that the gains in patenting are derived from structural and regional positions rather than to being simply a function of time spent in the network.

Drawing on research in economic geography, hypotheses 1 and 2 argued that proximity to other biotechnology firms and to public research organizations generates positive returns to innovation, and hypothesis 6 suggested that centrality may present contingencies to these effects. Our final model shows that being located near other firms has a marginally

6
The time lag between filing and issuing a patent in the life sciences is approximately two to three years, on average. Application counts may be underreported in later years of the analysis (1997–1999) because firms may have applied for patents that were not yet granted and recorded. In unreported sensitivity analyses, we ran the models with these time periods excluded (i.e., only the years 1989–1996) to ensure that no coefficient biases occurred from potential underreporting in later years. All coefficients remained similar in sign, magnitude, and significance, and the substantive results remained the same.

Table 3

Fixed-year Negative Binomial Regressions of Successful Patent Activity on Region, Firm, and Network-level Characteristics, 1989–1999 (N = 2,868)*

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Publicly held†	.26•••	.25•••	.26•••	.23•••	.22•••	.22•••
Age (years)	–.05••	–.05•	–.05••	–.04	–.04	–.04
Age squared	.001	.000	.001	.000	.000	.000
Collaborative experience (years)	.02•	.02	.02	.01	.01	–.002
Previous year patent count (logged)	1.15•••	1.15•••	1.15•••	1.07•••	1.07•••	1.07•••
Proximity$_{(firms)}$ (centered)		2.26••			1.60	2.63•
Proximity$_{(PRO)}$ (centered)			.02		–.01	–.02
Global position (centered)				.01•••	.01•••	.01•••
Global centrality × Proximity$_{(firms)}$						–.28•••
Global centrality × Proximity$_{(PRO)}$						.003•••
Constant	–.66•••	–.67•••	–.67•••	–.61•••	–.61•••	–.61•••
Chi-square	2938.3	3010.1	3031.3	2629.2	2681.7	2814.5
Degrees of freedom	17	18	18	18	21	23

• $p < .10$; •• $p < .05$; ••• $p < .01$; two tailed tests.
* All models include fixed-year effects.
† The reference category is privately held.

significant independent effect on rates of patenting ($p < .10$). The direct effect indicates that DBFs that are isolated from the global network but located near other biotech companies garner some additional benefits from their physical location. But the negative and significant interaction terms between centrality and proximity to firms complicates this story. The interaction suggests that firms that are closer to other firms receive less return to centrality than those in more isolated locations.

Being located near dense pockets of public research organizations, in contrast, does not exert a significant direct effect on innovation when included in the nested models, although this measure also reveals contingencies with centrality. Unlike proximity to other firms, the interaction between global centrality and proximity$_p$ in model 6 is positive. This is a notable finding, as it reveals that firms that are successfully able to prospect through diverse (and often far-flung) networks are also best able to gain from close access to information and resources developed in nearby public research organizations. Given the presence of a positive and significant interaction effect, the non-significant direct effect suggests that close proximity to public research spillovers is best exploited by those firms that have some degree of connectedness within the industry. Clearly, innovation benefits do not derive from simple proximity to sources of spillovers in the bio-medical field.

Hypothesis 3 proposed that linkages to well-connected firms would positively influence patenting, and model 6 supports this contention. Increasing global power centrality enhances patenting for all firms, regardless of physical location. The negative interaction between centrality and proximity$_f$, coupled with the positive interaction between centrality and proximity$_p$, however, suggests that the advantages of increasing global centrality are moderated by closeness to competitors and public-sector sources of spillovers. Firms that are near other firms receive less return from increasing their position in the global network than companies that are more isolated. In contrast, the models suggest that the firms that are able to capitalize the most on proximity to spillovers are those that are highly embedded in the industry network.

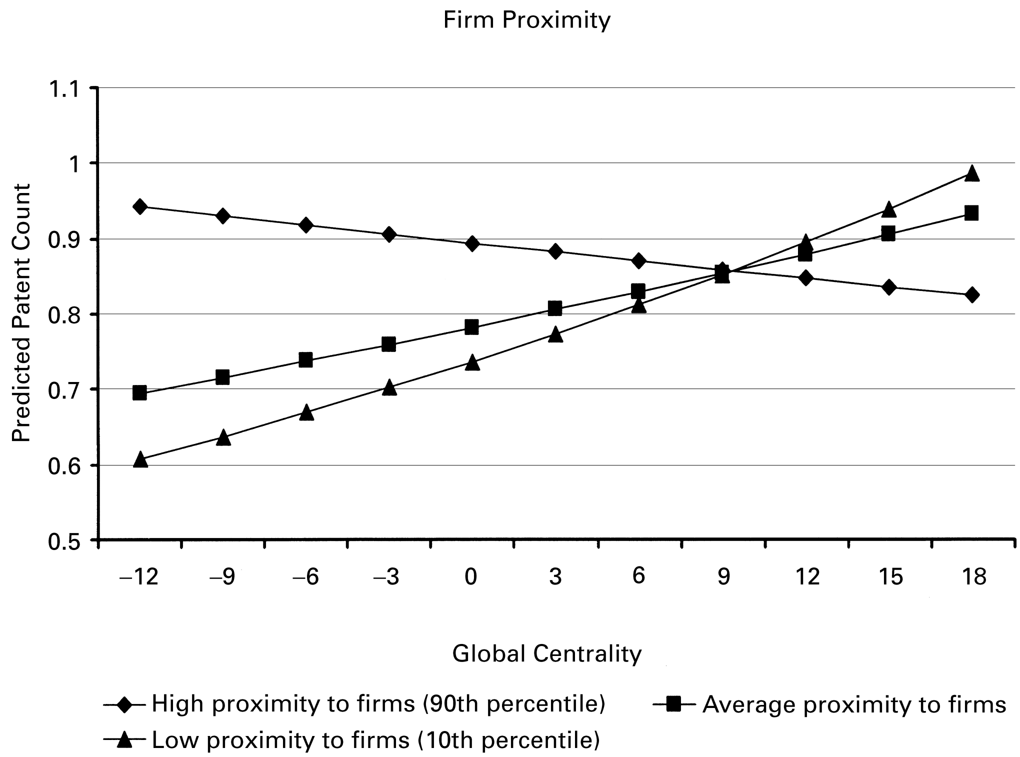
Using the coefficients from the final model—and keeping the value of the x axis in centered units to provide an easier interpretation of the mean values of global centrality (mean = 0)—figure 2 graphs the influence of increasing global network centrality on the predicted patent count of firms with three levels of proximity in the full sample: those at the 10th, average, and 90th percentile. As a point of comparison, biotechnology companies located in the three major regional clusters have substantially higher proximity scores than organizations located elsewhere. Boston, San Diego, and San Francisco Bay Area biotechs have average proximity_f scores that place them at the 85th percentile for the industry. These same companies are also closer to public research organizations, with average proximity_p scores at the 77th percentile.

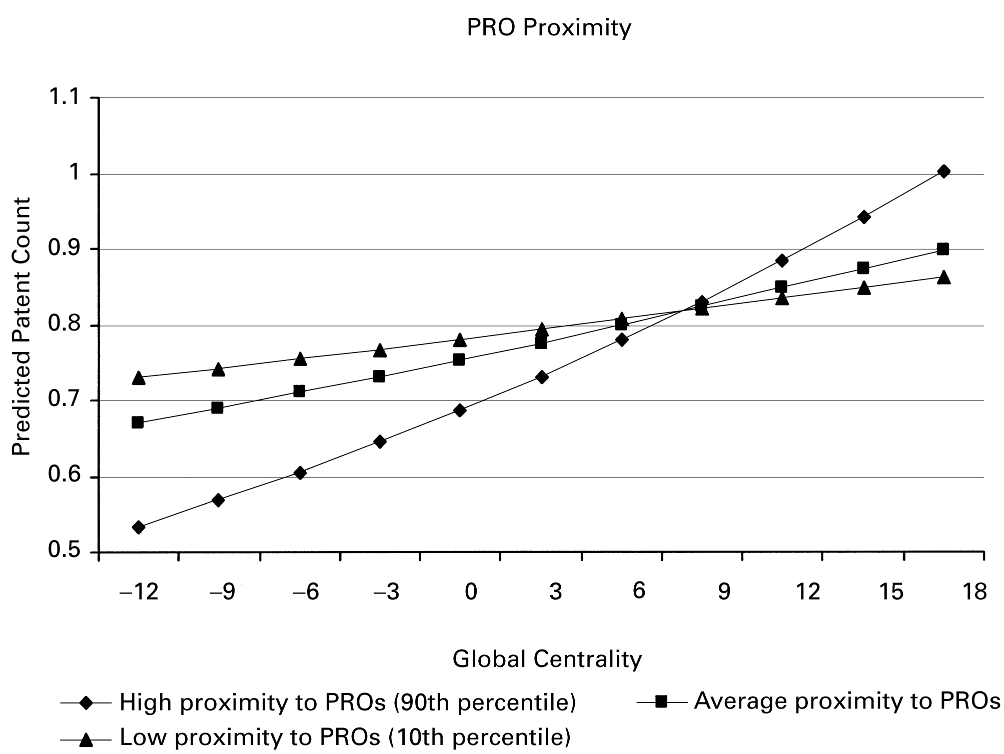
The top graph portrays the influence of centrality on companies at different levels of proximity to others in the industry. The graph shows that the beneficial effects of centrality are strongly moderated by propinquity. Highly proximate firms (i.e., 90th percentile) with a mean level of centrality patent significantly more (approximately 21 percent) than those that are geographically isolated (10th percentile). But the least clustered firms garner the greatest reward from increasing their position in the global network, and these firms surpass their most clustered competitors at the highest levels of centrality. The three lines cross at the 83rd percentile in centrality (a centered value of ~ nine). Thus the key implication of the graph is that proximity remains a positive delineator among firms, especially those with less than an 83rd percentile position in the network, but it is far from the sole provider of innovative advantages in the biotechnology industry.

The bottom graph in figure 2 depicts the relationship between global centrality and proximity to public research organizations. Interestingly, at mean levels of centrality, corresponding again to a null centered value, there is a slight discount (–12 percent) for firms that are extremely close to PROs compared with those that are far away. But the ability to access information and resources from nearby PROs increases as firms become more central in physically dispersed networks. Hence, centrality yields the greatest return when coupled with proximity to public-sector sources of scientific and technical know-how.

The combined effect of our proximity and centrality measures is revealing. Both graphs suggest that increasing centrality in the global industrial network is a key aid to discovery efforts and that distance to firms and other sources of information benefits moderate this effect. Where the model suggests that global centrality is a substitute for proximity to other firms, it implies that higher levels complement location near public-sector research organizations. A firm's ability to garner access to cutting-edge basic science may require the same

Figure 2. Predicted patent count as proximity increases, by three levels of global centrality.*





* All predicted counts are derived from the final model in table 3 and hold all control variables at their mean.

Table 4

Introducing Regional Controls to Fixed-year Negative Binomial Regressions of Successful Patent Activity on Region, Firm, and Network-level Characteristics, 1989–1999 (N = 2,868)*

Variable	Model 1	Model 2
Publicly held†	.25•••	.25•••
Age (years)	–.04	–.04
Age squared	.000	.000
Collaborative experience (years)	.01	–.004
Previous year patent count (logged)	1.07•••	1.06•••
$\text{Proximity}_{(firms)}$ (centered)	–1.00	.15
$\text{Proximity}_{(PRO)}$ (centered)	–.01	–.03
Global position (centered)	.01•••	.01•••
Global centrality × $\text{Proximity}_{(firms)}$		–.24•••
Global centrality × $\text{Proximity}_{(PRO)}$		.003•••
Regional controls‡		
Established regions (Boston, San Diego, and San Francisco Bay Area)	.28•••	.27•••
Nascent regions (Seattle, WA; Bethesda, MD: Raleigh-Durham, NC; Philadelphia, PA; New York greater metropolitan area)	.07	.08
Constant	–.80•••	–.81•••
Chi-square	2672.9	2820.5
Degrees of freedom	22	24

•• $p < .05$; ••• $p < .01$; two tailed tests.
* All models include fixed-year effects.
† The reference category is privately held.
‡ The reference category is non-agglomerated firm.

kind of capabilities that allow companies to successfully navigate globally dispersed networks.

We also argued that factors other than simple propinquity make regions fertile grounds for some biotechnology firms. Local connections spur the positive innovation returns associated with co-location. Table 4 presents the last two models of table 3, this time including a control for company location in Boston, San Diego, the San Francisco Bay area, and other nascent regional locations. The models show that firms located in the three established regions experience a significant and positive effect on innovation, whereas there is no additional innovative benefit for being located in a nascent region over other non-agglomerated locations.[7] In addition, including these regional controls reduces the effects of proximity to other firms, and the term becomes insignificant.[8] Thus the influence of propinquity appears to be largely related to the fact that Boston, San Diego, and the San Francisco Bay Area are especially fertile grounds for innovation. Location in these particular regions, rather than mere access to neighbors, appears to account for the direct proximity effects documented in table 3. A key to the consistently positive and significant effect of location in these three regions appears to be their dense internal alliance networks. These local structures are critical in distinguishing between physical agglomerations of firms and innovative clusters.

Local connectivity differs from propinquity in that it creates inequalities in co-located organizations' abilities to access key

7
We combined the regions into three categories (non-agglomerated, nascent (Seattle, WA, Bethesda, MD, Raleigh-Durham, NC, Philadelphia, PA, and the Tri-state area), and established (Boston, San Diego, and the San Francisco Bay area) but found similar trends if we disaggregate them and enter them separately. In current work, we analyze the key mechanisms that explain differences between established and nascent clusters (Powell, Packalen, and Whittington, 2010).

8
These effects might result from high levels of multicollinearity between the regional indicator and that of proximity. Because the bivariate correlation between those two measures is an acceptable .65, however, and VIFs and tolerances for the models in table 4 are within satisfactory ranges (< 5), it is unlikely this is due to statistical artifact.

Table 5

Fixed-year Negative Binomial Regressions of Successful Patent Activity on Region, Firm, and Network-level Characteristics, Regional Firms Only, 1989–1999 (N = 1,347)*

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
Publicly held†	.14	.13	.13	.13	.11
Age (years)	–.09•••	–.08••	–.09•••	–.07••	–.07
Age squared	.002••	.002	.002•	.002	.001
Collaborative experience (years)	.06•••	.04•	.06•••	.04•	.04
Previous year patent count (logged)	1.06•••	1.00•••	1.05•••	1.00	.99
$\text{Proximity}_{(firms)}$ (centered)	–1.07	–1.21	–1.00	–1.16	–1.13
$\text{Proximity}_{(PRO)}$ (centered)	–0.02	–0.01	–0.01	–0.01	–0.01
Global centrality (centered) (minus local ties)		.01••		.01••	.01•••
Local centrality (centered)			.02••	.01	.02•
Global centrality × Local centrality					–.002•••
Constant	–0.27	–0.23	–0.28•	–0.24•	–0.20
Chi-square	2233.70	1914.50	2237.13	1934.13	2048.82
Degrees of freedom	19	20	20	21	22

• $p < .10$; •• $p < .05$; ••• $p < .01$; two tailed tests.
* All models include fixed-year effects.
† The reference category is privately held.

information and resources within a region. That differentiation, we proposed in hypothesis 4, leads to wide variation in innovation rates within clusters and helps to explain why location in an established cluster may subject young or poorly connected firms to more intense competitive pressure (Stuart and Sorenson, 2003). We addressed this contention by focusing our second analysis on companies in the Boston, San Diego, and the San Francisco Bay area, again controlling for proximity to firms and spillovers and this time including measures for local and global centrality.

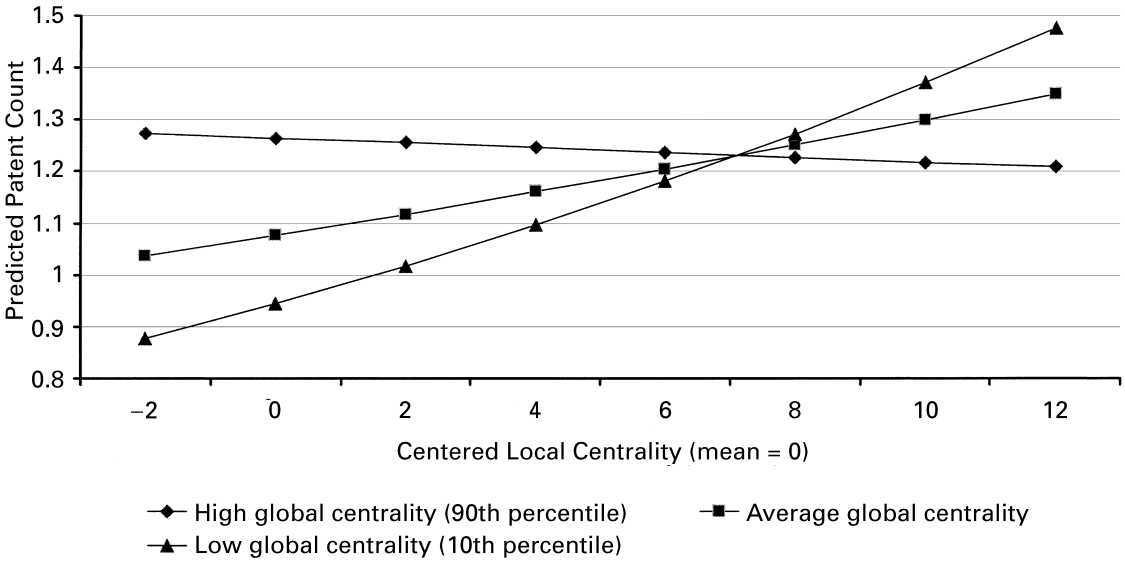
Regional Models

Table 5 presents the results from a series of fixed-year negative binomial count models, using the "regions only" sample. Model 1 reproduces model 5 in our first analysis (table 3), including coefficients for our control variables and proximity measures.[9] Models 2–4 incorporate main and direct effects for global and local centrality. Model 5 includes the interactive effects of local versus global centrality and is our final model.

Model 5 demonstrates that centrality in both global and local networks is associated with increased patent flows, offering support for hypothesis 4 and further bolstering hypothesis 3. This model also documents a modest negative interaction between the two measures, providing moderate evidence for hypothesis 5. In short, local and global networks exert distinct positive effects on innovation for regionally clustered firms, but there is a small reduction in direct influence when both are maximized. These results buttress the argument that both global and local networks make strong contributions to organizational innovation. In particular, companies receive independent rewards to patent flows from increasing centrality in their local network, as well as from their global connectivity. The joint effect of local and global centrality, though modest, suggests that the benefits of centrality are

9
We did not include the interactions between proximity and networks in the regional sample because there is much less variation in proximity between firms within regional boundaries. We include the direct effects in this table for completeness, but including the additional interaction variables does not change the substantive results of the table and, predictably, does not reveal significance for the interactions.

Figure 3. Predicted patent count as local centrality increases, by three levels of global centrality.*



* All predicted counts are derived from the final model in table 5 and hold the control variables at their mean.

somewhat discounted for firms that are highly connected in both realms.

Figure 3 graphs the effects of increasing local centrality for firms that are at the 10th, mean, and 90th percentile in global centrality. The graph shows that for most firms, particularly those that are not highly central globally, increasing either local or global centrality enhances innovation. In particular, organizations that are globally central with mean local centrality garner more of a patenting reward than similar companies that are less central in the industry-wide network. Even though we saw evidence of a modest substitutability effect between local and global centrality in the models, firms high on both accounts still gain more innovative return than with mean levels of both types of connectivity. Even though the interaction is statistically significant, its substantive importance seems questionable. The interactive effects of local and global centrality suggest, however, that firms with low and average global centrality gain the most from becoming more connected in the regional network structure. As the graph shows, although there are contingencies between the two measures, regionally co-located companies experience significant and positive gains from increasing both local and global connectivity.

We find scant support for conventional arguments about the innovative benefits of propinquity. In both our analyses, the direct effects of our proximity measures run counter to the hypothesized direction after controlling for centrality, key contingencies, and regional location. These results demonstrate that location in one of three key clusters is a source of advantage but show that these effects depend on the degree to which an organization is centrally connected, both within and beyond a home region. Closeness to concentrations of biotechnology companies provides the greatest advantages to firms that are less well-connected globally. Location near public-sector technical know-how becomes particularly propitious for innovation when there are dense, well-connected networks. Propinquity and centrality are both wellsprings of innovation, however, they offer at least partially exclusionary advantages. Thus understanding the effects of networks on innovation requires concern with physical location, and vice versa.

DISCUSSION

Both geographic and structural explanations for differential organizational advantage rest on ideas about relative position. Some geographic and network locations convey considerable benefits to the organizations that occupy them, while others do not. But organizations, like people, compete on a field that is simultaneously physical and social. Strategies aimed toward a single conception of location are quite likely to be lacking. Students of innovation would be well advised to consider multiple conceptions of location, because propinquity and centrality are intertwined, making the organizational orientations toward these different positions important factors in the equation linking networks, geography, and outputs. Our efforts at integration offer new ways to think about where to locate and how to connect.

Within regions, increasing one's centrality in local networks provides timely access to thicker, more tacit information conveyed among neighbors via more informal affiliations. Local networks may also enhance peer-to-peer monitoring among firms, generating strong benchmarking effects as companies gauge themselves by the performance of their neighbors. Thus the supportive context that develops in regional clusters may lower the coordination costs of local alliances without decreasing the flow of information through them. In contrast, increasing global centrality helps to situate a firm astride important resource and information flows that are vital for innovation. Organizations with better global positions can more easily reach across geographic distance in pursuit of novelty, and these opportunities can counterbalance the constraints of undue local homogeneity or lock-in.

One implication of this research is that differing degrees of geographic extension may lead otherwise similar network connections to exert distinct types of influence. Within regional boundaries, shared standards and norms of reciprocity often characterize relationships among participants. Local contractual networks thus serve to direct and perhaps amplify more informal information flows among co-located organizations. Outside of regional clusters, where information needs to cross considerable geographic distance, local norms and practices exert less influence because informal connections across organizational boundaries are sparser. Consequently, alliances and other formal interorganizational connections may operate more as conduits that transmit proprietary information from party to party, without supporting broader spillovers. Different logics may drive the workings of global networks and local regional clusters, and we find significant analytical purchase in distinguishing between them. Global and local networks may offer contingent benefits precisely because otherwise similar interorganizational ties operate differently in the two settings.

These findings presage a more integrative model of the social and geographic antecedents of innovation by suggesting that the density of ties inside a region may facilitate the development of relational governance mechanisms that increase the performance of proximate organizations. These "thick" ties can render local alliances more efficacious. This is not to say, however, that distant or global interorganizational ties are not salutary. Connections that reach out of and across regional clusters can provide key infusions of novelty that spur the development of good ideas (Burt, 2004). In network theories of innovation, the density of ties is often the mechanism by which firms enjoy governance benefits that foster cooperative exchanges of tacit knowledge, thus accruing innovation benefits. These results suggest that social ties are imbued with characteristics of regional agglomerations, and this combination results in significant performance benefits.

Another implication of our argument is that geographically distant ties are more likely to be characterized by less frequent or intimate connections, thus embodying traditional characteristics of weak ties. The distinct innovative relationships that develop locally and globally as a result of network and geographic distance suggest that proximity could be used to capture the strength of social ties more generally. By focusing on the collective influence of local and global ties, this research addresses criticisms of network research that take issue with its emphasis on structure to the exclusion of the character or nature of ties.

We reach beyond pure considerations of structure in two ways. First, we demonstrated that the physical proximity of partners alters the performance effects of otherwise similar network connections. Second, we showed that the relationship between proximity and centrality varies with the institutional form of nearby organizations. Being located close to corporate rivals yields different network effects than having lots of public research neighbors. Geography makes network effects contingent, but understanding the character of such contextual effects also requires attention to institutional variation.

Our results are suggestive for the study of regional clusters as well. An understanding of the factors that tip regions from supportive incubators into hotly contested arenas, or vice versa, requires attention to the shape of local networks. Policies designed to bolster regional economic development need to account for social structural as well as spillover effects. Many nascent biotech clusters appear to have the relevant ingredients but lack the glue and contacts necessary to catalyze them in productive ways. At the same time, understanding national sources of industrial leadership demands insight into how far-flung connections can transform geographically patchy industries into truly national collectives. The interplay of geography and networks speaks to the link between regional and national sources of economic growth in ways that beg deeper exploration.

Overall, our findings suggest three important addenda to the literature on regional agglomeration. First, the factors that account for innovative returns to location in the key regions of Boston, San Diego, and the San Francisco Bay area are relational rather than geographic. A crucial insight of our research is that what makes these regions region-like is their local networks. Second, the effects of proximity to important classes of organizations (other firms and public research organizations) varies with position in global interorganizational networks, suggesting the need for further work that treats clusters as ecologies comprising multiple organizational forms, which exist in different selection environments and hew to distinct institutional logics (Freeman and Audia, 2006; Audia, Freeman, and Reynolds, 2006). Finally, and most importantly, we find that the effects of physical location on innovation cannot be understood without seriously considering social structure. Both geographic and relational conceptions of location matter for innovation, but our results suggest that, at least in biotechnology, networks are primary.

Limitations

One counterweight to the findings is that our focus on the three regions introduces a selection bias that puts undue weight on the local network structure of regional firms, which may be more successful or innovative in general. Unfortunately, we have limited geographic information for the thousands of partner organizations of different types that make up the complete global network. Not only are there great challenges to obtaining this information around the globe, tough choices would be necessary to decide how to code branch offices and subsidiaries of organizations whose headquarters are located elsewhere. We did check for ties among biotech firms that are geographic neighbors, not located in the three largest regions. These three key regions are unusual because each has developed sizeable network components based on linkages among ostensible competitors, that is, direct ties between biotech companies. No other area of the country has more than sporadic, spotty local connections among firms. We cannot say that there are no local networks outside of the three regions that are anchored by non-firm partners, but in no other region in the U.S. do we find local networks knitted together by widespread collaboration among competing dedicated biotechnology firms.

There is also substantial variation on our dependent variable within the three focal regions. To be sure, some, but not all of the largest and most innovative firms in the industry are located in these clusters, but so are many struggling newcomers and limping incumbents. Rates of failure are high as well. Descriptive statistics in tables 1 and 2 show relatively few differences among regional and non-regional firms; these variables are also included in the models as controls. Although the models that underpin table 5 include no firms located outside the three focal regions, they also do not artificially truncate our dependent variable. Instead, we demonstrated that centrality in local networks distinguishes among firms that share a geographic location and, with it, similar scores on our proximity measures.

Our analyses indicate the need to draw more clearly defined linkages between the effects of propinquity and local network structure. Though we are tempted to argue that proximity is unimportant without the local connections that forge an agglomeration into a community, problems of data sufficiency force us to temper our claims. Instead, the pattern of findings reported in table 5 suggests that local centrality influences innovative output for firms in the same region. The results also indicate that global and local networks function differently because geographic proximity alters the ways in which otherwise similar formal relationships channel information and resources. This last claim is a key implication of the paper that begs further research.

Future Directions

Extensions of this research might examine the ways in which regionally bounded and globally dispersed networks are differently constituted, to more clearly specify how their successful navigation demands disparate competencies. The contractual ties that companies forge locally may be the relationships most apt to signal membership or engagement with a regional community, rather than connections that emphasize exclusivity or secrecy (through legal mechanisms, for example) to control or protect flows of information and resources. Thus regional ties may be more porous, and linkages among co-located partners may generate knowledge and skills that strengthen the overall region. Differences in the physical proximity of partners as well as their varied organizational forms can change the ways that interorganizational networks generate organizational and collective advantage.

In addition, regional clusters develop under circumstances unique to particular geographic locales, with distinctive institutional infrastructures and labor markets. More attention could be paid, for instance, to the lasting effects of distinctive institutional infrastructures and evolutionary trajectories. The three clusters we examined exhibit considerable heterogeneity with respect to their histories and contemporary dependence on different organizational forms, and that variation may generate important interregion differences. Though each cluster is home to at least one world-class research university, Boston draws on the clinical expertise associated with several elite teaching hospitals. The Bay Area cultivates intensive venture capital activity, and San Diego is distinguished by exemplary nonprofit research institutes—such as Salk, Scripps, and Burnham—that are more oriented toward translational research. The important roles these organizations play as anchors and intermediaries within their regions cannot be overstated, as they provide more open sources of information and knowledge than do proprietary firms and face fewer competitive selection pressures (Jong, 2006; Casper, 2007; Colyvas, 2007). Although proximity and social structure appear to operate similarly across the three established clusters, future research could deepen our understanding of the ways in which the histories of each region imprint a unique trajectory and influence on the ways in which networks and propinquity interact.

Lastly, we focused on innovation, but it would be valuable to study the interaction between proximity and social structure for additional outcomes, such as organizational stability, attainment or valuation, start-up company performance, or profitability. Future research can elucidate the ways in which the relational features of regions operate similarly or differently for alternative measures of performance.

Our work offers new insight into traditional arguments supporting geographic and network accounts of regional innovation. We showed that a key element of regional advantage for firms stems, in part, from the structure of a local interorganizational network. This regionally derived, yet relationally based concept is necessary to understand variations in the strength and effects of regional economies. Moreover, matching physical and relational conceptions of position more clearly specifies the mechanisms by which agglomeration enhances innovation. Examining regional effects on innovation in concert with network influences suggests that the fecundity of organizational R&D efforts may be driven by the interplay of both agglomeration and social capital. The secrets of industry are indeed in the air in a few propitious locales, but they also flow through network ties that structure relations and span distance, making knowledge flows anything but local.

REFERENCES

Adams, J.
2005 "Comparable localization of academic and industrial spillovers." In S. Breschi and F. Malerba (eds.), Clusters, Networks and Innovation: 379–408. Oxford: Oxford University Press.

Agrawal, A., and I. Cockburn
2002 "University research, industrial R&D, and the anchor tenant hypothesis." NBER Working Paper 9212.

Ahuja, G.
2000 "Collaboration networks, structural holes, and innovation: A longitudinal study." Administrative Science Quarterly, 45: 425–455.

Alderson, A. S., and J. Beckfield
2004 "Power and position in the world city system." American Journal of Sociology, 109: 811–851.

Allison, P. D., and R. P. Waterman
2002 "Fixed-effects negative binomial regression models." Sociological Methodology, 32: 247–265.

Almeida, P., and B. Kogut
1999 "Localization of knowledge and the mobility of engineers in regional networks." Management Science, 45: 905–917.

Arthur, W. B.
1994 Increasing Returns and Path Dependency in the Economy. Ann Arbor, MI: University of Michigan Press.

Asheim, B. T.
2000 "Industrial districts: The contributions of Marshall and beyond." In G. L. Clark, M. Feldman, and M. Gertler (eds.), The Oxford Handbook of Economic Geography: 413–431. Oxford: Oxford University Press.

Audia, P., J. H. Freeman, and P. D. Reynolds
2006 "Organizational foundings in community context: Instruments manufacturers and their interrelationship with other organizations." Administrative Science Quarterly, 51: 381–419.

Audretsch, D. B., and M. Feldman
1996 "R&D spillovers and the geography of innovation and production." American Economic Review, 86: 630–640.

Audretsch, D. B., and P. E. Stephan
1996 "Company-scientist locational links: The case of biotechnology." American Economic Review, 86: 641–652.

Bathelt, H., A. Malmberg, and P. Maskell
2004 "Clusters and knowledge: Local buzz, global pipelines and the process of knowledge creation." Progress in Human Geography, 28: 54–79.

Bengtsson, O., and S. A. Ravid
2009 "The importance of geographical location and distance on venture capital contracts." Available at SSRN: http://ssrn.com/abstract=1331574.

Bonacich, P.
1987 "Power and centrality: A family of measures." American Journal of Sociology, 92: 1170–1182.

Bresnahan, T., and A. Gambardella, eds.
2004 Building High-Tech Clusters: Silicon Valley and Beyond. Cambridge: Cambridge University Press.

Breznitz, S., and W. Anderson
2006 "Boston Metropolitan Area biotechnology cluster." Canadian Journal of Regional Science, 28: 249–264.

Brown, J. S., and P. Duguid
1991 "Organizational learning and communities of practice: Toward a unified view of working, learning, and innovation." Organization Science, 2: 40–57.
2000 The Social Life of Information. Boston: Harvard Business School Press.

Bulut, H., and G. Moschini
2006 "Patents, trade secrets, and the correlation among R&D projects." Economic Letters, 91: 131–137.

Burt, R. S.
1992 Structural Holes: The Social Structure of Competition. Cambridge, MA: Harvard University Press.
2004 "Structural holes and good ideas." American Journal of Sociology, 110: 349–399.

Cameron, A. C., and P. K. Trivedi
1998 Regression Analysis of Count Data. Cambridge and New York: Cambridge University Press.

Casper, S.
2007 "How do technology clusters emerge and become sustainable? Social network formation and inter-firm mobility within the San Diego biotechnology cluster." Research Policy, 36: 438–455.

Chesbrough, H. W.
2003 Open Innovation: The New Imperative for Creating and Profiting from Technology. Boston: Harvard Business School Press.

Cohen, W., R. R. Nelson, and J. P. Walsh
2000 "Protecting their intellectual assets: Appropriability conditions and why U.S. manufacturing firms patent (or not)." NBER Working Paper 7552.

Colyvas, J.
2007 "From divergent meanings to common practices: The early institutionalization of technology transfer at Stanford University." Research Policy, 36: 456–476.

Coriat, B., and F. Orsi
2002 "Establishing a new intellectual property rights regime in the United States: Origins, content and problems." Research Policy, 31: 1491–1507.

Crane, D.
1978 Invisible Colleges. Chicago: University of Chicago Press.

Davis, G., M. Yoo, and W. Baker
2003 "The small world of the corporate elite, 1982–2001." Strategic Organization, 1: 301–336.

Eisenhardt, K. M., and C. B. Schoonhoven
1996 "Resource-based view of strategic alliance formation: Strategic and social effects in entrepreneurial firms." Organization Science, 7: 136–150.

Feldman, M. P., and R. Florida
1994 "The geographic sources of innovation: Technological infrastructure and product innovation in the United States." Annals of the Association of American Geographers, 84: 210–229.

Fleming, L., C. King, and A. Juda
2007 "Small worlds and regional innovation." Organization Science, 18: 938–954.

Fleming, L., and M. Marx
2006 "Managing creativity in small worlds." California Management Review, 48 (4): 6–27.

Freeman, L. C.
1979 "Centrality in social networks: Conceptual clarification." Social Networks, 1: 215–239.

Freeman, J., and P. Audia
2006 "Community ecology and the sociology of organizations." Annual Review of Sociology, 32: 145–169.

Fujita, M., and P. Krugman
2004 "The new economic geography: Past, present and the future." Papers in Regional Science, 83: 139–164.

Galambos, L., and J. Sturchio
1996 "The pharmaceutical industry in the twentieth century." History and Technology, 13: 83–100.

Gambardella, A.
1995 Science and Innovation: The U.S. Pharmaceutical Industry during the 1980s. Cambridge: Cambridge University Press.

Gertler, M. S.
1995 "Being there: Proximity, organization, and culture in the development and adoption of advanced manufacturing technologies." Economic Geography, 71: 1–26.

Glaeser, E. L.
2005 "Re-inventing Boston: 1630–2003." Journal of Regional Science, 5: 119–153.

Granovetter, M.
1973 "The strength of weak ties." American Journal of Sociology, 78: 1360–1380.

Hagedoorn, J., and N. Roijakkers
2002 "Small entrepreneurial firms and large companies in inter-firm R&D networks—The international biotechnology industry." In M. A. Hitt et al. (eds.), Strategic Entrepreneurship: 223–252. Cambridge: Blackwell.

Hagedoorn, J., and J. Schakenraad
1994 "The effect of strategic technology alliances on company performance." Strategic Management Journal, 15: 291–309.

Hausman, J., B. H. Hall, and Z. Griliches
1984 "Econometric-models for count data with an application to the patents R and D relationship." Econometrica, 52: 909–938.

Henderson, R., A. Jaffe, and M. Trajtenberg
1998 "Universities as a source of commercial technology." Review of Economics and Statistics, 80: 119–127.

Ingram P., and P. Roberts
2000 "Friendships among competitors in the Sydney hotel industry." American Journal of Sociology, 106: 387–423.

Jacobs, J.
1961 The Death and Life of Great American Cities. New York: Random House.

Jaffe, A. B.
1986 "Technological opportunity and spillovers of research-and-development—Evidence from firm patents, profits, and market value." American Economic Review, 76: 984–1001.
1989 "Real effects of academic research." American Economic Review, 79: 957–970.

Jaffe, A. B., and M. Trajtenberg
2002 Patents, Citations and Innovations: A Window on the Knowledge Economy. Cambridge, MA: MIT Press.

Jaffe, A. B., M. Trajtenberg, and R. Henderson
1993 "Geographic localization of knowledge spillovers as evidenced by patent citations." Quarterly Journal of Economics, 79: 957–970.

Jong, S.
2006 "How organizational structures in science shape spin-off firms: The biochemistry departments of Berkeley, Stanford, and UCSF and the birth of the biotechnology industry." Industrial and Corporate Change, 15: 251–283.

Kenney, M.
1988 Biotechnology: The University-Industrial Complex. New Haven, CT: Yale University Press.

Kogut, B.
2000 "The network as knowledge: Generative rules and the emergence of structure." Strategic Management Journal, 21: 405–425.

Krugman, P.
1991 "Increasing returns and economic geography." Journal of Political Economy, 63: 483–499.

Malmberg, A., and P. Maskell
2006 "Localized learning revisited." Growth and Change, 37: 1–18.

Marshall, A.
1920 Industry and Trade. London: Macmillan.

Maskell, P., and A. Malmberg
1999 "Localized learning and industrial competitiveness." Cambridge Journal of Economics, 23: 167–186.

Mizruchi, M. S.
1992 The Structure of Corporate Political Action: Interfirm Relations and Their Consequences. Cambridge, MA: Harvard University Press.

Murray, F.
2002 "Innovation as co-evolution of scientific and technological networks: Exploring tissue engineering." Research Policy, 31: 1389–1403.

Myers, G.
1995 "From discovery to invention: The writing and rewriting of two patents." Social Studies of Science, 25: 57–105.

Nicholas, T.
2009 "Spatial diversity in invention: Evidence from the early R&D labs." Journal of Economic Geography, 9: 1–31.

Olson, G., and J. Olson
2000 "Distance matters." Human-Computer Interaction, 15: 139–178.

Orsenigo L.
1989 The Emergence of Biotechnology. New York: St. Martin's Press.

Owen-Smith, J., and W. W. Powell
2004 "Knowledge networks in the Boston biotechnology community." Organization Science, 15: 5–21.
2006 "Accounting for emergence and novelty in Boston and Bay Area biotechnology." In P. Braunerhjelm and M. P. Feldman (eds.), Cluster Genesis: Technology-Based Industrial Development: 61–86. Oxford: Oxford University Press.

Owen-Smith, J., M. Riccaboni, F. Pammolli, and W. W. Powell
2002 "A comparison of U.S. and European university-industry relations in the life sciences." Management Science, 48: 24–43.

Patton, D., and M. Kenney
2005 "The spatial configuration of the entrepreneurial support network for the semiconductor industry." R & D Management, 35: 1–16.

Perroux, F.
1950 "Economic space: Theory and applications." Quarterly Journal of Economics, 64: 89–104.

Pisano, G. P.
2006 Science Business: The Promise, the Reality, and Future of Biotech. Boston: Harvard Business School Press.

Podolny, J. M.
2001 "Networks as the pipes and prisms of the market." American Journal of Sociology, 107: 33–60.

Porter, K. A.
2004 "You can't leave your past behind: The influence of founders' career histories on their firms." Unpublished doctoral dissertation, Department of Management Science and Engineering, Stanford University.

Porter, M. E.
2000a "Location, competition, and economic development: Local clusters in a global economy." Economic Development Quarterly, 14: 15–34.
2000b "Locations, clusters, and company strategy." In G. L. Clark, M. Feldman, and M. Gertler (eds.), The Oxford Handbook of Economic Geography: 253–274. Oxford: Oxford University Press.

Portes, A.
1998 "Social capital: Its origins and applications in modern sociology." Annual Review of Sociology, 24: 1–24.

Powell, W. W.
1990 "Neither market nor hierarchy: Network forms of organization." In B. M. Staw and L. L. Cummings (eds.), Research in Organizational Behavior, 12: 295–336. Greenwich, CT: JAI Press.
1996 "Inter-organizational collaboration in the biotechnology industry." Journal of Institutional and Theoretical Economics, 152: 197–215.

Powell, W. W., K. W. Koput, and L. Smith-Doerr
1996 "Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology." Administrative Science Quarterly, 41: 116–145.

Powell, W. W., K. W. Koput, L. Smith-Doerr, and J. Bowie
2002 "The spatial clustering of science and capital." Regional Studies, 36: 299–313.

Powell, W. W., K. Packalen, and K. B. Whittington
2010 "Organizational and institutional genesis: The emergence of high-tech clusters in the life sciences." In J. Padgett and W. W. Powell (eds.), The Emergence of Organizations and Markets (forthcoming).

Powell, W. W., D. R. White, K. W. Koput, and J. Owen-Smith
2005 "Network dynamics and field evolution: The growth of interorganizational collaboration in the life sciences." American Journal of Sociology, 110: 1132–1205.

Putnam, R.
1993 Making Democracy Work: Civic Traditions in Modern Italy. Princeton, NJ: Princeton University Press.

Rhoten, D., and W. W. Powell
2007 "The frontiers of intellectual property: Expanded protection vs. new models of open science." Annual Review of Law and Social Science, 3: 345–373.

Romanelli, E., and M. P. Feldman
2006 "Anatomy of cluster development: Emergence and convergence in the US human biotherapeutics, 1976–2003." In P. Braunerhjelm and M. P. Feldman (eds.), Cluster Genesis: Technology-Based Industrial Development: 87–112. Oxford: Oxford University Press.

Romanelli, E., and O. Khessina
2005 "Regional industrial identity: Cluster configurations and economic development." Organization Science, 16: 344–358.

Saxenian, A.
1994 Regional Advantage: Culture and Competition in Silicon Valley and Route 128. Cambridge, MA: Harvard University Press.

Shan, W. J., G. Walker, and B. Kogut
1994 "Interfirm cooperation and startup innovation in the biotechnology industry." Strategic Management Journal, 15: 387–394.

Singh, J.
2005 "Collaborative networks as determinants of knowledge diffusion patterns." Management Science, 51: 756–770.

Song, J., P. Almeida, and G. Wu
2003 "Learning-by-hiring: When is mobility more likely to facilitate interfirm knowledge transfer?" Management Science, 49: 351–365.

Sorenson, O.
2005 "Social networks and the persistence of clusters: Evidence from the computer workstation industry." In S. Breschi and F. Malerba (eds.), Clusters, Networks, and Innovation: 297–316. Oxford: Oxford University Press.

Sorenson, O., and P. Audia
2000 "The social structure of entrepreneurial activity: Geographic concentration of footwear production in the United States, 1940–1989." American Journal of Sociology, 106: 424–461.

Sorenson, O., and L. Fleming
2004 "Science and the diffusion of knowledge." Research Policy, 33: 1615–1634.

Sorenson, O., and T. E. Stuart
2001 "Syndication networks and the spatial distribution of venture capital investments." American Journal of Sociology, 106: 1546–1588.
2008 "Bringing the context back in: Settings and the search for syndicate partners in venture capital investment networks." Administrative Science Quarterly, 53: 266–294.

Sorenson, O., and D. M. Waguespack
2006 "Social structure and exchange: Self-confirming dynamics in Hollywood." Administrative Science Quarterly, 51: 506–589.

Stuart, T. E.
2000 "Interorganizational alliances and the performance of firms: A study of growth and innovation rates in a high-technology industry." Strategic Management Journal, 21: 791–811.

Stuart, T. E., H. Hoang, and R. Hybels
1999 "Interorganizational endorsements and the performance of entrepreneurial ventures." Administrative Science Quarterly, 44: 315–349.

Stuart. T. E., and O. Sorenson
2003 "The geography of opportunity: Spatial heterogeneity in founding rates and the performance of biotechnology firms." Research Policy, 32: 229–253.

Suchman, M.
1995 "Localism and globalism in institutional analysis: The emergence of contractual norms in venture finance." In W. R. Scott and S. Christensen (eds.), The Institutional Construction of Organizations: 39–63. Thousand Oaks, CA: Sage.

Uzzi, B.
1996 "The sources and consequences of embeddedness for the economic performance of organizations: The network effect." American Sociological Review, 61: 674–698.

Walker, G., B. Kogut, and W. J. Shan
1997 "Social capital, structural holes and the formation of an industry network." Organization Science, 8: 109–125.

White, H. C.
1981 "Where do markets come from?" American Journal of Sociology, 87: 517–547.

Zucker, L. G., and M. R. Darby
1996 "Star scientists and institutional transformation: Patterns of invention and innovation in the formation of the U.S. biotechnology industry." Proceedings of National Academy of Science, 93: 709–716.

Zucker, L. G., M. R. Darby, and M. B. Brewer
1998 "Intellectual human capital and the birth of U.S. biotechnology enterprises." American Economic Review, 88: 290–306.