Knowledge Networks as Channels and Conduits: The Effects of Spillovers in the Boston Biotechnology Community

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We contend that two important, nonrelational, features of formal interorganizational networks—geographic propinquity and organizational form—fundamentally alter the flow of information through a network. Within regional economies, contractual linkages among physically proximate organizations represent relatively transparent channels for information transfer because they are embedded in an ecology rich in informal and labor market transmission mechanisms. Similarly, we argue that the spillovers that result from proprietary alliances are a function of the institutional commitments and practices of members of the network. When the dominant nodes in an innovation network are committed to open regimes of information disclosure, the entire structure is characterized by less tightly monitored ties. The relative accessibility of knowledge transferred through contractual linkages to organizations determines whether innovation benefits accrue broadly to membership in a coherent network component or narrowly to centrality. We draw on novel network visualization methods and conditional fixed effects negative binomial regressions to test these arguments for human therapeutic biotechnology firms located in the Boston metropolitan area.

Key words: knowledge networks; economic geography; spillovers; biotechnology; patenting

Introduction

A central tenet of the new economic sociology is that networks are both the wellsprings and the "plumbing" of markets (White 1981, 2002; Powell 1990; Burt 1992; Podolny 2001). Whether operationalized in terms of informal ties among individuals (Granovetter 1985, Uzzi 1996), interlocking affiliations among corporations (Mizruchi 1992, Davis et al. 2003), or formal, contractually defined, strategic alliances (Eisenhardt and Schoonhoven 1996, Powell et al. 1996), networks are an essential component of markets because they channel and direct flows of information and resources from position to position within a social structure.

The conceptualization of networks as "pipes" underscores the strategic benefits that accrue to well-situated individuals, organizations, and collectivities because of their position at the confluence of information and resource flows. This conception has proven highly fertile in explaining a wide range of organizational, economic, and social phenomena. Nevertheless, limited attention has been paid thus far to how important nonstructural features—such as the characteristics of the organizations that represent nodes in a network, geographic location, or the institutional underpinnings of the larger structure—alter the character of information flows.

We begin with a consideration of the varied ways in which formal contractual alliances might be understood to channel information and resource flows between organizations, arguing that these linkages can represent either "open" channels or more proprietary, "closed" conduits. We then turn to a discussion of two nonstructural considerations that might affect the accessibility of formal contractual pipelines. We draw on economic geography to link a more unfettered conception of information flow to the well-established benefits of regional industrial agglomeration (Romer 1986, Krugman 1991, Anselin et al. 1997). We turn next to organizational theory, and the sociology and economics of science, to argue that the characteristics of the dominant nodes in a network can alter the flow of information throughout the entire structure. We contend that integrating considerations of the geographic propinquity of network structures and the institutional demography of network nodes offers new insights into the relationship between social structural position and firm-level outcomes. Moreover, this conception contributes to the development of an organizational network theory that is sensitive to diverse meanings of location and to the varied institutional arrangements that typify complex organizational fields.

Networks as Both Channels *and* Conduits

Social connections among individuals and the various linkages among organizations can be conceptualized in two general terms. We posit a pair of logical possibilities. The first sees linkages as channels that diffusely and imperfectly direct transfers between nodes, facilitating information spillovers (and other externalities)

that benefit both loosely connected and centrally positioned organizations. An alternative conception represents pipelines as closed conduits, characterized by legal arrangements (e.g., nondisclosure agreements and exclusive licensing contracts that transfer intellectual property rights) designed to ensure that only the specific parties to a given connection benefit from the information that is exchanged. While the former interpretation suggests that "weak" connections among participants in a network may offer returns to its members in terms of spillovers from network channels, the latter understanding implies that centrality and "strong" connections involving tighter, more proprietary conduits are the primary sources of competitive advantage derived from networks. The literature on interorganizational linkages has, to date, emphasized the latter view over the former.

Organizations collaborate within their own industries, as well as across sectors, for both strategic and social purposes (Eisenhardt and Schoonhoven 1996). Such partnerships represent the "plumbing" of the market, and the strategic benefits of location in dense alliance networks have been well documented. Powell et al. (1996) characterize such diverse industry networks in biotechnology as the "locus of innovation," emphasizing the positive benefits of increased rates of learning and access to knowledge on a rapidly developing research frontier. To test ideas about organizational learning, many researchers have focused on the relationship between strategic alliance networks and innovative outputs in the form of patents.

Hagedoorn and Schankenraad (1994) demonstrate a positive relationship between the formation of technology partnerships and firm-level innovation. Shan et al. (1994, Walker et al. 1997) provide evidence that strategic alliance networks increase patent rates for biotechnology firms. Stuart (2000) also finds that technology-based alliances predict innovation rates in the semiconductor industry, but he demonstrates that the effects of those affiliations depend strongly on partner characteristics. Similarly, Ahuja (2000) draws on a variety of network indicators to examine the relationship between position in strategic alliance networks in the international chemical industry and patenting outcomes, finding a beneficial effect of direct network connections on innovative outputs.

These works largely spotlight the effects of technology-based network ties among competitor firms in the same industry. Research on innovation in biotechnology, which attends much more to the diverse set of institutions engaged in basic research and product development, has assessed the implication of ties to diverse types of partners, particularly universities and research institutes (Powell 1996, Owen-Smith et al. 2002). While reiterating the importance of connections among firms, this line of research offers somewhat mixed findings

on the role that ties among different types of organizations play in the biotechnology industry. Shan et al. (1994), for instance, find a positive effect of firm-to-firm alliances on biotech patenting but not a significant effect of R&D agreements with universities. George et al. (2002), however, observe that firms with ties to universities produce more patents and have lower R&D costs than those lacking such ties. Similarly, Arora and Gambardella (1990) demonstrate that pharmaceutical ties to small biotechnology firms and universities represent complementary strategies for innovation.

The literature on networks and innovation emphasizes the strategic benefits of formal connections, conceptualized as focused pipelines, while underplaying the role of ties to noncommercial organizations as well as the social aspects of alliances. Such collective benefits have been found for many other types of networks, however (Powell 1990). Buyer-supplier networks in industrial districts in the "Third Italy" (Piore and Sabel 1984) and in the Manhattan garment industry (Uzzi 1996, 1997) have been shown to offer benefits to connected partners by channeling information and resources and by locating members in a dense communal web of overlapping affiliations and obligations. In these settings, inclusion in a collectivity whose boundaries are defined by both network connections and geographic propinquity is crucial to organizational performance.

In a similar vein, work examining board-of-director interlocks among firms underlines the extent to which such ties contribute to the development and maintenance of a corporate elite (a geographically dispersed, largely closed, and self-replicating community), where membership speeds the transmission of novel management practices (Davis and Greve 1997) and similar patterns of corporate political involvement (Mizruchi 1992). Moreover, recent examinations of cohesiveness as a key indicator of network embeddedness (Moody and White 2003) demonstrate that membership in coherent network components generates benefits net of more directly specified measures of centrality. Across these cases, connections among firms are conceptualized as offering both positional and membership benefits. We contend that formal alliances among diverse organizations in a science-based industry may convey innovation benefits, either as diffuse channels for information spillovers or as proprietary pathways for directed information and resource transfer between partners.

More specifically, when strategic alliances represent unfettered channels for information transfer, membership in a loosely connected but coherent network topology imparts significant advantages to firms in knowledge-intensive industries. For example, Murray (2002) emphasizes joint authorship, the movement of students and post-doctoral fellows, and positions on scientific advisory boards as less structured mechanisms of knowledge transfer. She points to the sharing of

resources and equipment and collective access to a larger scientific group as key features of knowledge communities. In contrast, secure, tight conduits that transfer information in a focused manner between parties yield innovation benefits only to those organizations that are centrally positioned in a network structure. Put simply, the network conduits view focuses on point-to-point transmission in which benefits are garnered only by the nodes at the end of the pipes. However when pipelines are "leaky"—either due to membership in a regional economy or because of the normative practices of key members of the network—They function more like sprinklers, irrigating the broader community. This irrigation metaphor, drawn specifically from work in economic anthropology on cooperative agricultural practices (Lansing 1991, Scarborough et al. 1999), underscores the collective benefits derived from membership in a community rich in relational linkages.

Economic Geography and Institutional Demography

Both the geographic location of organizations connected by formal ties and the institutional characteristics of nodes in a network may alter the character of information flows. Propinquity is commonly linked to a variety of information spillovers. In addition, organizations vary in the extent to which they adhere to the institutional and legal rules designed to prevent the diffusion of information beyond the parties to a formal tie.

The evidence for geographically concentrated knowledge flows in research-intensive industries is compelling. Studies drawing on ethnographic analysis (Saxenian 1994) and patent citation data have demonstrated that: (1) knowledge spills across organizations more readily when they are colocated (Jaffe et al. 1993, Almeida et al. 2003); (2) the size and mobility of the science and engineering labor pool in a region increases localized spillovers (Almeida and Kogut 1999); and (3) strategic alliances among firms increase the likelihood of such spillovers (Almeida et al. 2003).

Research on the biotechnology industry has documented that the geographic colocation of firms is a function of access to scientific talent and the skills of "star" scientists who are active in both academic and commercial research communities (Audretsch and Stephan 1996, Zucker and Darby 1996). In high technology regions, the secrets of industry may not be floating freely in the air (Marshall 1920), but they are situated in informal communities of practice that constitute a local technology labor market (Brown and Duguid 1991).

In sum, we argue that formal ties among regionally agglomerated organizations are important in accounting for innovation to the extent that they signal membership in a local technological community. Such membership offers firms access to information transmitted through informal network channels in the region, while raising a firm's visibility in competitive local labor markets for technically trained employees. Conceptualizing formal ties as a means to access informal communities emphasizes the public character of relationships and illuminates the importance of community membership above and beyond the specifics of structural position. To formalize these ideas, we suggest:

PROPOSITION 1. *Membership in a geographically colocated network will positively effect innovation, but centrality in the same network will have no effect.*

PROPOSITION 2. *Centrality in a geographically dispersed network will positively effect innovation, but membership per se will have no effect.*

Another potential source of network openness lies in the dependence of regional economies, and high technology industries more generally, on diverse organizational forms. Indeed, the strength and robustness of U.S. high technology regions lies in their joint reliance on the contributions of both public and private research organizations (Owen-Smith et al. 2002). Even when individual alliances may be sealed by a partner's commitment to proprietary norms, the dominance of the larger network by organizations that pursue open science can render the overall structure more accessible. When public research organizations anchor networks, even those concerned with commercial applications, the systems manifest greater spillovers.

Public research organizations (PROs), such as universities and nonprofit institutes, increasingly conduct research that is both advanced scientifically and immediately valuable to industry. This class of organizations differs from research-intensive firms on two key dimensions. Institutional differences between PROs and for-profit organizations stem from: (1) their disparate approaches to rules for the dissemination and use of scientific findings (Dasgupta and David 1987, 1994; Owen-Smith 2003), and (2) sharply divergent selection environments.

Two related strands of thought offer insights into the effects of these distinctive institutional regimes. First, Nelson (1981, 1986) emphasizes the key role that organizational diversity plays in the development of knowledge on a research frontier, emphasizing the importance of public research institutions to the generation of innovation. New knowledge flows out of universities much more readily than it does from commercial organizations (Jaffe et al. 1993). Similarly, sectors in which noncommercial organizations are prominent in early stage research activities promote more open technological trajectories (Dosi 1982). Some high-technology sectors—most notably biotechnology—owe their rapid emergence to the robustness and expansiveness that PROs add to networks (Powell 1996).

A second feature of PROs is their durability and resilience. Public entities, such as universities or government institutes, do not routinely fail or merge. Thus, they contribute to the stability of highly volatile technological fields. In contrast to firms, which are subject to potentially strong market pressures and experience liabilities of newness and obsolescence, PROs add a presence that is focused on longer term criteria of evaluation. PROs also promote information transmission because they adhere to the norms of the open information disclosure characteristic of public science. The implication of these two lines of argument is that networks centered on PROs should yield greater benefits to general community membership than to specific structural position. Consequently, we propose:

PROPOSITION 3. *In networks dominated by PROs, membership will positively effect innovation, but centrality will have no effect.*

PROPOSITION 4. *In networks dominated by commercial entities, centrality will positively effect innovation, but membership will have no effect per se.*

We turn to an examination of an institutionally diverse biotechnology region, the greater Boston, Massachusetts, area, to examine patterns of information flow.

Propinquity and Centrality in Biotechnology

The biotechnology industry exemplifies many of the general features of science-based sectors. Biotechnology firms in the United States and Europe are clustered in a small number of geographic regions and are strongly dependent on public research organizations, such as universities, for skilled labor and novel scientific competencies (Audretsch and Stephan 1996, Anselin et al. 1997, Zucker and Darby 1996). These firms are embedded in multiple networks of strategic alliances and gain competitive advantage from continuous scientific and technical innovation (Powell et al. 1996). Access to new knowledge and capabilities in this field occurs both via localized information spillovers and through diverse strategic alliance networks that are international in scope.

Consequently, geographic propinquity and network centrality represent substantively different locations in a field where the ability to innovate determines survival. One goal of this paper is to bridge the gap between geographic and network explanations for innovation rates of biotechnology firms. An important aspect of this question involves the diversity of organizational forms located in different regions, thus our second purpose is to examine the relationship between the institutional demography of nodes and network effects on innovation.

Biotechnology is a field where all the relevant capabilities are seldom found under a single organizational roof (Powell and Brantley 1992). The field had its origins in university labs, where research was supported by decades of substantial government investment in R&D. As the field developed, universities, nonprofit research centers, major research hospitals, and start-up firms all had a hand in moving research from the lab into clinical development. On the financing side, venture capital firms bankrolled many of the small firms, and large, multinational corporations later joined in as they came to see the merits of new, more directed methods of drug discovery (Henderson and Cockburn 1996, Malerba and Orsenigo 2002). Until very recently, we did not find all these types of organizations located in physical proximity, so the maturation of the industry involved reaching out across regional clusters to access diverse resources.

These varied participants represent more than novel combinations of organizations, however. We suspect that the combination of the responsiveness of private firms and the dedicated resources of public organizations is crucial to the generation of novel technologies. To examine this idea, we analyze patenting by dedicated human therapeutic and diagnostic biotechnology firms (DBFs) located in the Boston metropolitan area, an important regional cluster for the U.S. biotechnology industry. We first introduce the Boston region—highlighting the scale of biotechnology activity and the diversity of organizational forms and selection environments in the area. We examine the network ecology of the region as a means to test our general propositions about the relationship between propinquity, institutional diversity, network position, and innovation.

Why Boston?

We examine the relationship between local and nonlocal network position and patent volume for DBFs located in the Boston metropolitan area, which is home to one of the largest concentrations of biotechnology firms in the world (Stuart and Sorenson 2003). In addition to DBFs, however, Boston boasts a rich population of public research organizations, including public and private universities (e.g., Harvard, MIT, and the University of Massachusetts), independent research institutes (e.g., the Dana Farber Cancer Institute), and research hospitals (e.g., Massachusetts General Hospital). Finally, numerous venture capital (VC) firms are also located in the Boston region.[1]

The joint presence of a sizeable number of DBFs, PROs, and VCs makes Boston the most organizationally diverse regional cluster in the U.S. biotechnology industry. The considerable heterogeneity of organizational forms in Boston (public,[2] nonprofit, private; large and small) coincides with a diverse set of selection environments. By diversity we mean variation in both organizational form and mission. These varying approaches to innovation and information dissemination are linked, so

that they constitute a local organizational field or knowledge community. Boston is a strong candidate for a geographic region where information could diffuse widely and informally through a thriving technological community and labor market.

At the same time, the institutional diversity of the organizations that populate this region offers the possibility for an examination of the effects that node demography has on innovation. Because PROs are primarily focused on nonproprietary academic research, they are "leakier" organizations than firms. Thus their diversity and number may increase spillovers within a region by rendering even formal network ties more diffuse. Boston area venture capitalists are also more likely to invest locally than are VC firms in the Bay Area, the other densely populated biotechnology cluster (Powell et al. 2002). This type of ecology produces an environment where we expect firms to derive innovation benefits from membership in a weakly connected, but coherent network "community."

Two possibilities are immediately apparent. First, formal network connections among colocated organizations may be unlocked by the broader externalities that accompany propinquity. Alternatively, partnerships may act as channels that direct information flows while emitting spillovers due to a community's dominance by organizations dedicated to a more academic, or public research mission. We first describe the data set and sources that afford a test of these alternative propositions, then turn to network visualization methods to portray the evolution of the Boston network, mapping its transition from a strong anchor in PROs to a more proprietary network dominated by commercially oriented nodes. This transition, we argue, allows us to discriminate between two possible sources of "openness" in formal network pipelines: geographic propinquity and institutional demography.

Interorganizational Networks in Biotechnology

Data Sources. Our primary explanatory data are drawn from a relational dataset of formal network connections involving 482 dedicated biotechnology firms for the period 1988–1999.[3] The data on firms and interorganizational arrangements were coded from BioScan, an industry publication that reports information on firms and the formal arrangements in which they are involved. The organizational data include firm age, size, public status, and (where applicable) reasons for exit. Tie data allow us to calculate measures of network experience, diversity, and centrality, and to classify individual ties by the type of business activity (R&D, Finance, Commercialization, Licensing) they entail.[4] These data represent yearly "snapshots" of the formal network that constitutes the "locus of innovation" in biotechnology (Powell

et al. 1996). Our dependent variable, a count of patents assigned to those corporations, was developed using the U.S. Patent Office's online database.

Defining the Networks. Our focus is on the geographic and organizational conditions affecting information flows through formal networks. Our database enables us to develop two different networks.[5] The first, which we dub "Boston," includes only organizations located in the region and the ties among them. In this group are 58 DBFs, 19 PROs, and 37 VC firms. We observe 201 formal contractual relationships, including R&D partnerships, licensing deals, commercialization and marketing arrangements, and investment ties among these 114 organizations over the period 1988–1999.

The second network, which we label "Boston+," comprises all organizations in any locations that have a network tie to a Boston-based organization. The Boston+ network then places Boston-area DBFs in a global network without reference to the physical location of their partners. The Boston+ network includes 212 DBFs, 96 PROs, 240 VC firms, 24 government agencies, and 168 pharmaceutical/chemical/healthcare companies.[6] We observe 1,559 ties among these 740 organizations during the period 1988–1999. This latter network includes all organizations in the Boston region, but excludes the ties that make up the Boston network.

We argue that formal ties among Boston organizations are important in explaining innovation primarily to the extent that they enable access to informal spillovers within a regional ecology. Such membership offers, for instance, access to information transmitted through local labor markets for Ph.D. life scientists. Thus formal ties are more open than their portrayal as pipelines suggests. The suggestion that interorganizational alliances sometimes function more as channels than as conduits represents a departure from approaches to innovation networks that rely on measures of direct and indirect linkages among organizations.

Ahuja (2000) demonstrates that indirect connections among chemical firms positively affect innovation, though the effect is moderated by the number of direct ties. The logic underlying Ahuja's finding is straightforward, relating the number of organizations (and thus network pipelines) that a focal node can access to the variety of information it can gather. In this view, network reach carries innovation benefits by enabling firms to access information that their partners have gathered through focused network connections. These benefits, however, are greater for firms that are themselves party to relatively few alliances. Research emphasizing the importance of such indirect connections is predicated on knowledge spillovers from nodes (in this case, information transferred by a tie between two other organizations is accessible to ego via its own partnership).

Local Membership, Trans-Local Centrality. Despite the established importance of network reach, our emphasis on the signaling effects of formal ties adds an additional dimension to analyses of information transmission through networks. We contend that informal regional networks and open institutional regimes alter the extent to which formal connections direct and restrict information flows. While the nodes in a network transmit information at one remove, more transparent pipelines distribute information both to partners and to other organizations that are not party to the alliance. The primary analytic challenge for this view is to discern the minimal level of affiliation that might convey access to such spillovers. We focus our empirical attention on membership in the largest weakly connected component in a given network. This structure, the "main component," represents membership in a loosely linked but coherent community. Such membership, we contend, offers a channel to the widest available range of information flows (spillovers from ties) while increasing a firm's visibility in local labor markets and in informal networks among scientists. To the extent that regional agglomeration effects open network ties, membership in the main component of the Boston network will increase a firm's ability to tap into information flows. Following Proposition 1, concerning the salutary effect of membership in a geographically colocated network, the specific corollary for the Boston network is: Connection to the main component will positively effect the volume of patents successfully prosecuted by local DBFs, while centrality will have no effect.

In contrast, we expect that informal channels for information transfer will be much less salient in larger, geographically dispersed networks. Where the partners in a relationship are physically distant, weaker informal networks and greater monitoring difficulties will close formal contractual ties, limiting the extent to which information might be accessible to the surrounding community. Under these conditions, position in the formal plumbing of the market, rather than membership in a weakly connected community, will yield information benefits. We thus take the analogy relating networks to pipes carrying information and resources seriously, arguing that position in geographically dispersed networks will increase firm-level innovation. Where physical distance limits the openness of network avenues, centrality at the convergence of multiple, tightly bounded conduits will enable access to knowledge transmitted directly from partner to partner. Centrality makes organizations an obligatory passage point for the information flowing through a network structure. Under these conditions, membership confronts a firm with a web of opaque linkages it has few means to tap. Thus, the formalization of Proposition 2 suggests that centrality in the more dispersed Boston+ network will have a positive effect on patent volume, while main component membership will have no effect.
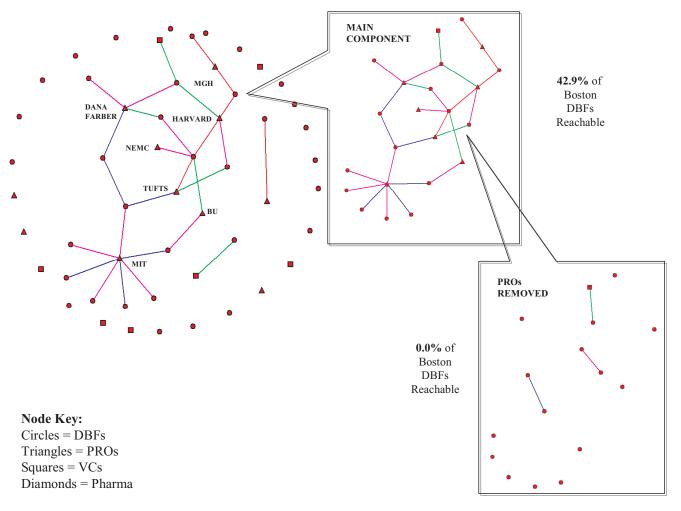
Our argument to this points hinges on the differential role that connections to a weak component play in networks that vary by propinquity. Proximity, however, is only one possible factor in network accessibility. We have also argued that the institutional underpinnings of a network (that is, the extent to which it is dominated by divergent organizational forms) will alter the role that alliances play in innovation. In particular, we contend that networks dominated by public research organizations will manifest innovation effects characterized more by membership than by position. Due to their commitment to the norms of open science, public sector organizations weaken the contractual strictures that close formal alliances and thus contribute to the irrigation of the larger community. To further develop this line of argument, we provide visualizations of the Boston and Boston+ networks.[7] These visualizations reveal differences across location, and also demonstrate that the evolution of the Boston network is well suited to an analytic approach designed to partial out geographic and organizational sources of network openness.

Images of the Boston Networks. Figure 1 presents a series of images of the Boston network in 1988. The shape of nodes in the network represents organizational type—triangles represent PROs, circles indicate DBFs, squares reflect the position of venture capital firms. Red nodes are organizations located in Boston. The color of ties reflects the type of activity they involve—red = R&D, green = financial, blue = commercialization, and magenta = licensing.

Note several interesting features of Figure 1. First consider the Boston network at the upper left. In 1988 this network was relatively sparse with the bulk of organizations isolated from the network of formal relationships.[8] The ties that do exist form a dominant weakly connected network component.[9] More interestingly, note the critical role that PROs (triangles) play in connecting the main component of the network and the relative absence of VC firms. (There are few squares, and only one is connected even peripherally to the main network corridor.) Six public research organizations (MIT, Boston University, Tufts, Harvard, the Dana Farber Cancer Center, Massachusetts General Hospital, and the New England Medical Center) appear in the most connected cluster of organizations. In 1988, then, the Boston biotechnology community was only sparsely connected internally by formal collaborations. While the network contains nearly 43% of active Boston area DBFs, the main component is heavily dependent for its cohesiveness on key public research organizations.[10] Removing these organizations from the network results in the complete collapse of the main component.

Figure 2 represents the Boston+ network in 1988. Notice first that this network is both larger and much
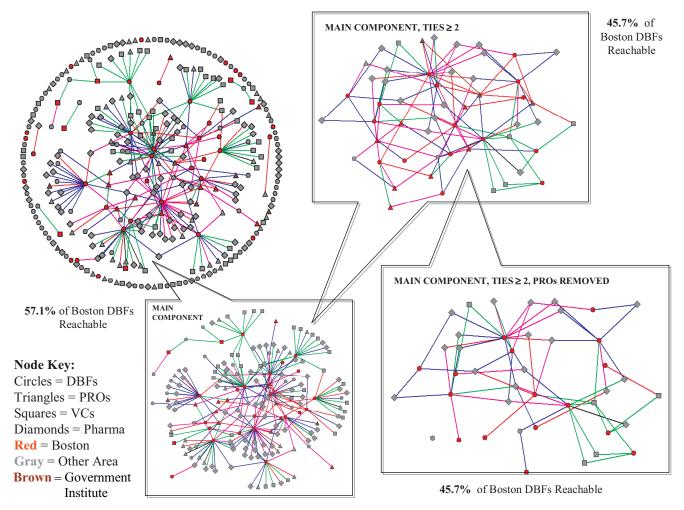
Figure 1   Boston Network, 1988

more organizationally diverse than the Boston network, due to the inclusion of government agencies (represented by brown triangles) and large pharmaceutical companies (represented by gray diamonds). The complete Boston+ network in the upper left quadrant of Figure 2 is also strikingly different visually. While the Boston-only network is a sparse corridor, strongly reliant on PROs for cohesiveness, the Boston+ network is dominated by hub and spoke configurations where otherwise isolated VCs and large pharmaceuticals connect to individual Boston area DBFs. The main component of the network contains more than 57% of Boston biotech companies. More firms in the area are reachable through trans-local network connections than through local ties. These external linkages offer a variety of benefits, including access to capital, approaches and solutions to problems different from those used locally, and downstream support in new product development.

The great majority (67%) of the 182 organizations connected to this component have only one tie. To visually explore the cohesiveness of this network, we remove those organizations. The resulting image is more densely

and redundantly bonded than the Boston structure. Note that this network is dependent for its cohesiveness on two distinct types of organizations. To disconnect this component, *both* Boston area PROs *and* external large corporations must be removed from the network. Removing only one type of organization (we remove PROs in the final call-out of Figure 2) shrinks the main component somewhat, but does so without disconnecting any Boston DBFs from the core of the network.

Figures 1 and 2 suggest that, early in its development, the Boston biotechnology community was weakly linked with less than half of all local DBFs reachable through network channels. The early coherence of this regional network stemmed from the active participation of local public research organizations. Extending the network to include physically distant partners, and thus greater organizational diversity, highlights the extent to which venture capital firms and large companies from outside the region reach in and attach to Boston area biotechs. These outside ties also altered the composition of the main component, reducing its structural dependence on local research organizations. Nevertheless, this

Figure 2   The Boston+ Network, 1988

MAIN COMPONENT, TIES ≥ 2

45.7% of Boston DBFs Reachable

57.1% of Boston DBFs Reachable

MAIN COMPONENT

Node Key:
Circles = DBFs
Triangles = PROs
Squares = VCs
Diamonds = Pharma
Red = Boston
Gray = Other Area
Brown = Government Institute

MAIN COMPONENT, TIES ≥ 2, PROs REMOVED

45.7% of Boston DBFs Reachable

increased network robustness may well have come at the expense of open information flow. Large pharmaceutical companies and research universities put scientific findings and intellectual property to very different uses.

The evolutionary pattern in which for-profit technological progress springs from public sector roots proposed by Nelson (1981, 1986) appears to hold for the Boston network. Consider Figure 3, which presents two simple descriptive statistics for the Boston and Boston+ main components. Figure 3 represents (1) the percentage of ties in each component that connect DBFs to PROs in a given year, and (2) the percentage of Boston area biotech firms that are members of the main component in each year.
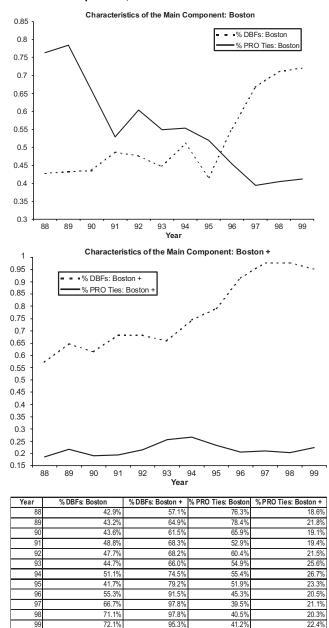
Figure 3 suggests a qualitative change in the Boston network's level of dependence on ties involving public research organizations across the period covered by the data but implies no such transition for the Boston+ network. The shifts reflected in Figure 3 capture an important transition in the institutional foundations of

the Boston biotechnology community, highlighting the growing role of for-profit organizational forms in the local community. As a point of comparison, Figure 4 reprises Figure 1 to present a series of minimum-energy representations of the Boston network in 1998.[11]

By 1998 more than 71% of Boston DBFs were connected to this component. More importantly, the network itself has undergone a marked change as local biotech firms began working directly with one another, rather than forming indirect "chains" through shared connections to PROs. Local VC firms are now much more active in the network, which is notably apparent in the portion of the corridor to the right of MIT. PROs (particularly MIT, BU, Harvard, and Brigham and Women's Hospital) still play an important role in the network in 1998, but their dominance is decreasing, as evidenced by the image of the component with PROs removed.

Consider the final frame of Figure 4, which illustrates that nearly 30% of Boston DBFs remain connected in a component that does not rely on public organizations. Indeed, the growth of biotech-to-biotech ties and the

Figure 3   Characteristics of the Boston and Boston-Plus Main Components, 1988–1999

Year	% DBFs: Boston	% DBFs: Boston +	% PRO Ties: Boston	% PRO Ties: Boston +
88	42.9%	57.1%	76.3%	18.6%
89	43.2%	64.9%	78.4%	21.8%
90	43.6%	61.5%	65.9%	19.1%
91	48.8%	68.3%	52.9%	19.4%
92	47.7%	68.2%	60.4%	21.5%
93	44.7%	66.0%	54.9%	25.6%
94	51.1%	74.5%	55.4%	26.7%
95	41.7%	79.2%	51.9%	23.3%
96	55.3%	91.5%	45.3%	20.5%
97	66.7%	97.8%	39.5%	21.1%
98	71.1%	97.8%	40.5%	20.3%
99	72.1%	95.3%	41.2%	22.4%

increasing support of local VCs suggest that Boston is undergoing a transition from its early dependence on PROs to a more market-oriented regime, where small science-based firms play a connective role similar to the ones held by large companies in the trans-local network.

This modification occurs within the local network, but no similar alteration is apparent trans-locally. This qualitative shift in the node demography of the Boston network offers the opportunity to test multiple sources of network openness. If PRO-based networks are more open than those dominated by proprietary organizations,

then we expect (following Propositions 2 and 3) that membership in the Boston main component will positively affect patenting, while a central position in the Boston+ network will positively influence innovation. However, if PRO dominance maintains the openness of formal network connections, then the growing importance of local DBFs and VCs will be reflected in more closed connections. Such closure will limit spillovers in the network, curtail membership effects on innovation, and increase the effect of centrality. Thus, the application of Proposition 3 for Boston suggests that: As a network's reliance on firms increases, centrality in the network will have a positive effect on patent volume.

If, on the other hand, propinquity drives the level of spillovers expected in a formal alliance network (regardless of institutional features), then the Boston network's changing levels of reliance on PROs should have no effect on the structure's openness. Hence, we expect no change in the effect of local centrality on innovation and, following Proposition 4, we contend that: As the Boston network's reliance on firms increases, centrality in the network will have no effect on patent volume.

We turn to a conditional-fixed-effects negative binomial regression of an 11-year pooled cross-section of firm-level patent data for the 58 Boston area DBFs to test these hypotheses.
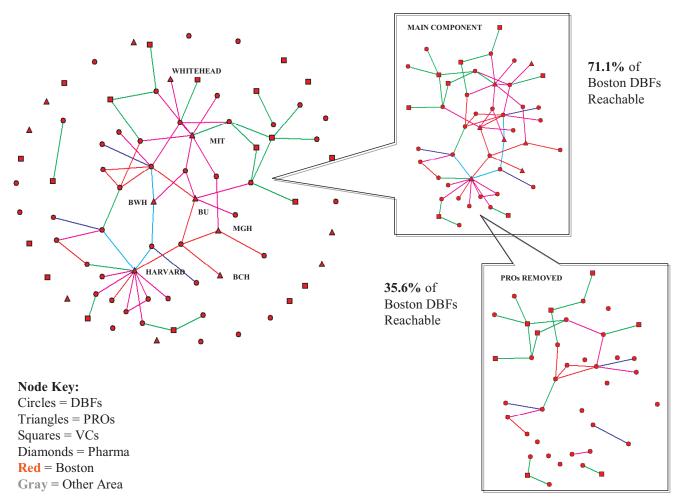
Models and Methods

Network Variables

Independent Variables. Several network measures derived from the Boston and Boston+ networks provide the independent variables for this analysis. The first, which we call *membership*, is a dummy variable set to one if a firm has at least one tie to the largest weakly connected component of the network in a given year. This variable operationalizes our conception of membership in a loosely linked, coherent community. We calculate this measure independently for both the Boston and the Boston+ networks.

Our second variable, *position*, is an indicator of network centrality based on Freeman's (1977, 1979) measure of betweeness, which captures the extent to which firms sit astride network pathways between other organizations.[12] Betweeness centrality, then, indicates a firm's ability to absorb (or interrupt) information flows through tightly sealed network pipes. We calculate betweeness for both the Boston and Boston+ networks. In the latter case, the measure is calculated on a geographically dispersed network that excludes ties among Boston area organizations. Finally, we include a multiplicative interaction between Boston area betweeness and a time period dummy variable to indicate the differential effects of centrality in a network anchored by PROs (time period = 0) and by firms (time period = 1).

Figure 4 Boston Network, 1998

71.1% of Boston DBFs Reachable

35.6% of Boston DBFs Reachable

Node Key:
Circles = DBFs
Triangles = PROs
Squares = VCs
Diamonds = Pharma
Red = Boston
Gray = Other Area

Control Variables. We also include a variety of organizational and network control variables. Firm level controls include a dummy variable indicating whether a company is publicly traded in a given year, age and a quadratic age term in years, and a variable measuring firm size (operationalized as the log of the number of employees). Network controls are designed to clarify the effects of membership and centrality. We include two additional network measures that we expect to effect firm patenting along with their multiplicative interaction. First, *Boston R&D Ties: PRO* is a simple count of research and development ties connecting Boston DBFs and PROs in a given year.[13] Similarly, *Ties to NIH Complex* is simply the number of ties connecting Boston firms to the National Institutes of Health and its subagencies in Bethesda, Maryland.* All models are estimated in a conditional fixed effects framework with firm and year effects to control for unobserved heterogeneity across organizations and time. Table 1 defines our variables and relevant interaction terms, while the Appendix presents descriptive statistics and a correlation matrix.

Model Specification. We model counts of patents by application date in an 11-year pooled cross-section for a panel of 58 DBFs located in the Boston metro area, employing a conditional fixed-effects negative binomial specification (Hausman et al. 1984, Cameron and Trivedi 1998) to correct for over-dispersion in patent counts.[14] Such models also control for unobserved heterogeneity by estimating effects using only within firm variation. Thus, these models drop firms with no year-to-year variation in patent rates.

Results

Table 2 reports findings from a series of regressions that test Hypotheses 1–4. Model 6 is the best fitting.

Local Membership, Nonlocal Position. Our first two hypotheses address the differential role formal network ties play within and outside an established high technology region. Hypothesis 1, that connection to the Boston area main component positively effects patenting, finds support in all models. The second component of the hypothesis, that local position will have no effect, finds

Table 1   Variable Labels and Definitions

Variable	1	Definition
Dependent Variable		
# Patents (application)		Yearly count of successful patent applications
Independent Variables		
Boston membership		Dummy variable, 1 = connected to the main network component in Boston network
Boston position		DBF betweeness centrality score, Boston network
Boston+ membership		Dummy variable, 1 = connected to the main component in the Boston+ network
Boston+ position		DBF betweeness centrality score, Boston+ network (Boston ties removed)
Time period		Dummy variable, 1 = 1993–1998
Time period × Boston position		Interaction between a time period dummy variable (1 = 1993–1998) and Boston position
Controls		
Public		Dummy variable, 1 = publicly traded firm
Age		Age in years since firm founding
Age^2		Age in years since firm founding, squared
Log(size)		Log(number of employees)
Boston R&D ties: PRO		Number of R&D ties to Boston Area Public Research Organizations
Ties to NIH complex		Number of ties (all types) to the National Institutes of Health and subagencies
Boston R&D ties: PRO × NIH Ties		Interaction between number Boston R&D ties to PROs and a dummy variable capturing the presence of one or more ties to the NIH and subagencies

support only in models that do not include time period interactions, suggesting that institutional and propinquity effects may be interdependent. Likewise, Proposition 2, which predicts that centrality will increase patenting for the Boston+ network, is also supported in all model specifications.

The implication of Hypothesis 1 is clear. Within a major regional biotechnology community, collaborations among organizations matter for explaining the innovative outputs of firms. Such ties, we contend, are important

to the extent that they signal membership in a local technological community. A weak connection to the diffuse formal ties that constitute the main component of the local network enables firms to capture geographically bounded information spillovers by providing an entry ticket to rich informal networks of academic and industrial scientists, while also raising visibility in the local labor market.[15] We also find negative (Models 1–3) and nonsignificant (Models 4–6) effects of membership in the larger and more diverse Boston+ main compo-

Table 2   Conditional Fixed-Effects Negative Binomial Regressions of Successful Patent Applications, 1988–1998

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Public (SE)	−0.090 (0.190)	−0.090 (0.190)	−0.075 (0.190)	−0.044 (0.189)	−0.015 (0.190)	0.003 (0.189)
Age	0.190 (0.081)*	0.190 (0.081)*	0.223 (0.083)**	0.149 (0.088)	0.145 (0.089)	0.193 (0.090)*
Age^2	−0.008 (0.003)*	−0.008 (0.003)*	−0.010 (0.003)**	−0.006 (0.003)	−0.006 (0.003)	−0.009 (0.004)*
Log(size)	0.679 (0.132)**	0.679 (0.132)**	0.657 (0.132)**	0.654 (0.130)**	0.656 (0.130)**	0.633 (0.129)**
Boston main component	0.376 (0.118)**	0.376 (0.118)**	0.368 (0.118)**	0.413 (0.118)**	0.425 (0.119)**	0.411 (0.119)**
Boston betweeness	−4.328 (3.589)	−4.328 (3.589)	−10.420 (5.275)*	−4.768 (3.671)	−6.914 (3.867)	−15.626 (5.992)**
Boston+ component	−0.585 (0.258)*	−0.585 (0.258)*	−0.556 (0.259)*	−0.363 (0.277)	−0.459 (0.277)	−0.471 (0.277)
Boston+ betweeness	15.960 (4.257)**	15.960 (4.257)**	14.001 (4.420)**	9.689 (4.789)*	10.892 (4.794)*	9.521 (4.832)*
Time period		−2.142 (0.569)**	−2.286 (0.559)**	−1.940 (0.601)**	−1.918 (0.600)**	−2.103 (0.579)**
Time period × Boston betweeness			11.019 (6.519)			14.520 (7.161)*
Boston R&D ties: PRO				0.132 (0.106)	0.325 (0.135)*	0.392 (0.138)**
NIH ties				0.172 (0.061)**	0.197 (0.061)**	0.186 (0.061)**
Boston R&D PRO × NIH ties					−0.317 (0.152)*	−0.436 (0.164)**
Constant	−4.073 (1.004)**	−1.931 (0.683)**	−1.967 (0.682)**	−1.913 (0.690)**	−1.794 (0.699)*	−1.798 (0.697)**
Pseudo R^2	0.445	0.450	0.452	0.456	0.459	0.461
Log likelihood	−441.748	−441.749	−440.274	−436.742	−434.604	−432.464
N	337	337	337	337	337	337

Note. *$p < 0.05$; **$p < 0.01$.

Pseudo R^2 is calculated manually relative to an intercept-only model of patent applications.

All models include fixed firm and year effects.

nent. This weak finding is suggestive of the difficulties that firms might face in capturing information flows through membership in a web of opaque connections. Where main component ties signal community membership locally, in a physically dispersed and institutionally diverse network of tightly monitored conduits, a comparable weak connection might be more akin to a competent minor leaguer attempting to play in the majors while lacking the necessary skills.

Hypothesis 2 also carries a clear message. In the Boston+ network, physical distance and the dominance of organizations committed to proprietary uses of knowledge render formal ties more closed, limiting the viability of informal network and labor market mobility as mechanisms for information transfer. Local codes of conduct and rules for interaction are unlikely to extend outside a region where point-to-point transmission of information through proprietary linkages is typical. Under these circumstances, being situated at the intersection of numerous formal pipelines enhances firm-level knowledge outputs. Model 6 provides clear support for Propositions 1 and 2, relating differences in the geographic dispersion of formal alliance networks to variations in patterns of information flow and thus in innovation.

To take the irrigation analogy one step further, consider a system where the "leakiness" of information and resource pipelines is dependent on the types of nodes through which ideas typically pass. In Boston, for instance, the great majority of structurally important paths flow through PROs committed to open norms of information disclosure. In contrast, the Boston+ network is anchored by multiple types of organizations that share varying commitments to proprietary uses of information. If node demography is important to the maintenance of loosely fettered formal ties, then the qualitative change in the Boston network's reliance on PRO ties (documented in Figures 1, 3, and 4) suggests that as the importance of proprietary information channels grows in the region, we should see an increasing effect of local network position.

Hypothesis 3 predicts just this effect. We test the hypothesis by use of a multiplicative interaction between local betweeness centrality and a dummy variable set to one for the period 1993–1998. This variable is interpretable as the effect of local centrality on patenting in the later half of our time period.[16] The main effect of Boston position, similarly, can be understood to represent the effect of local betweeness centrality in the early years of the time series. Finally, the main effect of time period represents the effect of a betweeness centrality score of zero (reflecting either an isolate or a firm with only one tie) in the later time period. We find consistent support for Hypothesis 3. As the Boston biotechnology community shifted from structural reliance on PROs towards dependence on for-profit organizations

(DBFs and VCs), local centrality began to generate benefits for innovation. Specifically, Model 6 coefficients for the Boston position and the time period interaction variable suggest that in the early part of the time series a standard deviation increase in betweeness centrality was associated with a 23% *decrease* in expected patenting. In contrast, the same standard deviation increase in centrality in the second half of the time series implies a 28% *increase* in expected patenting. Not surprisingly, this transition is accompanied by a negative effect of having a very low centrality score in the last half of our time series.

Consider also the interesting, though not hypothesized, negative main effect of the Boston position. This finding may reflect the aspects of power and arbitrage captured by betweeness centrality. In addition to enabling firms to appropriate information flows, high betweeness offers the possibility for firms to interrupt or alter transmissions to the detriment of their partners. The betweeness measure then offers two possibilities for arbitrage: a negative form where powerfully positioned middlemen extract value by interrupting or distorting information and a more positive form where cupids pass information on to distantly positioned network alters.

The robust negative effect of Boston position in models including time period interactions suggest that negative brokerage efforts by firms may be actively punished in communities dominated by PROs.[17] While still only suggestive, one implication of this finding is that opportunistic behavior on the part of firms embedded in networks dominated by PROs magnifies the negative externalities that can be associated with playing a tertius role. Such "punishment" may take multiple forms, such as university limitations on connections to "pushy" commercial firms or resistance by partners to more stringent legal mechanisms to "close" alliances to limit spillovers. Similarly, aggressive strategic use of a powerful structural position in the context of a more community-oriented network may limit access to informal information flows as scientists working in "academic" institutional regimes tend to shy away from proprietary limitations on the use of their findings.

Hypothesis 4—that increased local reliance on firms will not effect patenting—is not borne out by our best fitting model. This hypothesis, however, represents a strong form of our argument as it implies that either geographic propinquity or node demography may alter the flow of information through a network structure. Model 6, however, demonstrates that this is not the case. Consider the robustly positive effect of membership in the Boston main component (net of both local centrality *and* direct R&D ties to local PROs). The strong support that Model 6 provides for Hypotheses 1 and 3 implies

that both propinquity and institutional characteristics—two attributes of formal interorganizational networks that are independent of structure—transform network effects on information flow. Both attributes of network nodes in the Boston biotechnology community affect the relationship between network position and access to spillovers.

Conclusion and Implications

Our results demonstrate the importance of considering nonrelational features of networks that remake the character of information transmission through a formal topology. These findings also indicate the extent to which formal partnerships between organizations represent the outcroppings of informal social relationships in a community. In sum, we find that two attributes—geographic propinquity and the institutional characteristics of key members in a network—transform the ways in which an organization's position within a larger network configuration translates into advantage. This effect is driven, we contend, by variations in the security of the network ties themselves. The extent to which information transmitted through formal linkages is accessible is a function of: (1) the extent to which ties are embedded in a dense, regional web of formal and informal affiliations, and (2) whether the nodes that anchor a network pursue public or private goals. These findings suggest that studies of innovation should take into account the dual importance of physical location and institutional anchors. We contend that the joint examination of propinquity and centrality links economic geography's emphasis on concentrated information spillovers with economic sociology's focus on knowledge flows through an abstract social topology.

Emphasizing key organizational features of network nodes, in contrast, reminds us that the institutional and legal arrangements that secure directed information transmission are an outcome of participant commitments and efforts. Independent of propinquity effects, we find that differences in the composition of network participants shift the relationship between centrality and innovation. In more general terms, this finding represents a first step towards blending network and institutional approaches, thus illuminating the central role of key nodes in a network as carriers of the rules and practices. We present a relatively simple typology of node types, considering only the extent to which an organization conducts research under academic or proprietary institutional regimes. The practices and commitments of network nodes can be sharply divergent, with one set of organizations emphasizing open science rather than restricted relationships. Under such conditions, dominant logics emerge at the level of both networks and communities. Transparent modes of information transfer will trump more opaque or sealed mechanisms

when a significant proportion of participants exhibit limited concern with policing the accessibility of network pipelines.

To pursue the image we employ, closed conduits offer reliable and excludable information transfer at the cost of fixity, and thus are more appropriate to a stable environment. In contrast, permeable channels rich in spillovers are responsive and may be more suitable for variable environments. In a stable world, or one where change is largely incremental, such channels represent excess capacity. The implications of both node characteristics and network features are then deeply conditioned by environmental volatility, and this possibility has not been well attended to in literatures relating network position to organizational outcomes.[18]

Moreover, proprietary arrangements can come to dominate once open architectures as fields stabilize and innovation becomes less radical. Indeed, this is a common evolutionary pattern in the emergence of new sectors and one that has shaped a variety of industrial and technological trajectories. Examining the conditional effects of institutional regimes and network topologies on industrial and regional development opens the possibility that institutional factors and propinquity may contribute to studies of emergence, maintenance, and change in networks and sectors. At the same time, attending to interdependencies across categorical features of nodes and structural features of networks implies that research relating central positions to outcomes may do well to account for the presence and role that multiple organizational forms play in the constitution and maintenance of innovation systems. While we limit our consideration to the effects of organizational commitments in an existing network, concern with the dominance of different logics of appropriateness offers a new set of tools to examine structural and technological change, an approach that emphasizes normative rules guiding partner selection and access to information systems of varying opacity.

Appendix. Descriptive Statistics and Correlations

	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 # Patents (application)	2.756	4.693	0.000	36.000	1.000													
2 Public	0.656	0.476	0.000	1.000	0.130	1.000												
3 Age	8.903	4.893	0.000	29.000	0.099	0.170	1.000											
4 Age²	103.139	112.428	0.000	841.000	0.059	0.046	0.953	1.000										
5 Log(size)	4.420	1.079	1.099	8.132	0.454	0.470	0.325	0.223	1.000									
6 Boston membership	0.493	0.501	0.000	1.000	0.060	0.140	0.021	−0.028	0.215	1.000								
7 Boston R&D ties: PRO	0.147	0.528	0.000	4.000	0.053	0.013	0.137	0.097	0.117	0.243	1.000							
8 Boston position	0.007	0.017	0.000	0.130	−0.026	0.033	0.075	0.037	0.178	0.378	0.309	1.000						
9 Time period	0.575	0.495	0.000	1.000	0.110	0.238	0.192	0.181	0.013	−0.011	−0.072	0.003	1.000					
10 Time period × Boston position	0.004	0.014	0.000	0.130	0.004	0.105	0.093	0.073	0.118	0.272	0.103	0.754	0.244	1.000				
11 Boston+ membership	0.898	0.304	0.000	1.000	0.016	0.211	−0.124	−0.185	0.159	0.333	0.094	0.133	0.025	0.096	1.000			
12 Ties to NIH complex	0.685	1.330	0.000	8.000	−0.030	0.066	0.020	−0.019	0.064	0.159	−0.016	0.052	−0.104	0.070	0.174	1.000		
13 Boston+ position	0.021	0.020	0.000	0.100	0.180	0.229	0.099	0.017	0.448	0.405	0.128	0.386	−0.054	0.375	0.343	0.420	1.000	
14 Boston R&D ties: PRO × ties to NIH	0.042	0.296	0.000	3.000	0.047	0.009	0.041	0.011	0.112	0.144	0.533	0.104	−0.147	0.030	0.048	0.154	0.270	1.000

Endnotes

[*]The NIH is the largest funder of biomedical R&D in the world, and the primary recipients of its grants are PROs. R&D grants to commercial biotech firms are a relatively new phenomenon and reflect the research capacities of DBFs.

[1]We follow *Pratt's Guide to Venture Capital Sources* and focus on venture companies that are oriented toward high risk, high involvement, early stage investment in entrepreneurial firms. *Pratt's* does not include angel investors, pension funds, or university technology offices in the category of VCs. In our database on venture capital, we have measures of company age, capitalization, number of offices, and whether the firm primarily invests its founder's own money or other investors' money. In previous work (Powell et al. 2002) we documented the dramatic growth of venture capital disbursements to biotechnology companies in the 1990s. In Boston, the great bulk of VC financing was local until 1996, when external financing from Bay Area VCs expanded. Some of these VCs opened branch offices in Boston, but given their (relatively) late arrival on the scene, we code their location as outside of Boston. Researchers working on venture capital financing have yet to sort out the allocation of decision-making responsibilities between home offices and branch locations.

[2]Both government agencies (e.g., the National Institutes of Health) and universities might be considered "public." However, because of their different funding roles, we separate government institutes from universities, nonprofit research institutes, and hospitals by assigning such agencies to the category "Government." No federal research institutes are located in the Boston region.

[3]We define DBFs as independently held, profit seeking firms involved in human therapeutic and diagnostic applications of biotechnology.

[4]Our data draw on the April edition of *BioScan*, in which new information is added for each calendar year.

[5]For further details on the database from which these data are derived, see Powell et al. 1996, pp. 124–129; Powell et al. 2004.

[6]The Boston+ network is more diverse in terms of organizational forms than the Boston network because neither government institutes nor large pharmaceutical/chemical/healthcare companies (such as Merck or Eli Lilly) were located in the Boston metropolitan area during the time period covered by our dataset. This remains true for government laboratories, but large pharmaceutical companies such as Novartis have recently announced plans to relocate R&D facilities in the Boston region in hopes of taking advantage of precisely the community effects we postulate above (Palmer 2002). While the pattern is changing, very few of either of these forms of organizations are located in *any* of the established biotechnology clusters in the United States.

[7]We use Pajek, a freeware program developed by Vladimir Batagelj and Andrej Mrvar, to develop meaningful and replicable visual representations of these two networks. Pajek implements two minimum-energy, or spring-embedded, network drawing algorithms based on graph theoretic conceptions of distance and the physical theory of random fields (Guyon 1995). We draw on these two algorithms (Kamada and Kawai 1989, Fruchterman and Reingold 1991) to create images that position nodes by appeal to the overall pattern of connections in the network. These images locate isolates on the periphery of the image while situating more connected nodes centrally. For more information on the algorithms or their use for visualization, see Owen-Smith et al. (2002), Powell et al. (2004), and http://vlado.fmf.uni-lj.si/pub/networks/pajek.

[8]Isolates are placed at the periphery by the drawing algorithms we employ.

[9]In every year for which we have data, both the Boston and Boston+ networks are characterized by a large network component of this sort.

[10]Recent work on the development of strategic alliance ties and their role in innovation has emphasized the importance of more cohesive networks as opposed to networks rich in structural holes (Walker et al. 1997, Ahuja 2000). As Ahuja frames the argument, ego networks rich in structural holes negatively effect patenting because such networks tend to reduce trust, hindering the free flow of information and limiting network-channeled spillovers.

[11]We do not present a visualization of the Boston+ network in 1998 because change in this network from 1988 to 1998 represents quantitative growth in the main component, but not a qualitative shift in its demography.

[12]We use betweeness centrality rather than degree centrality so we can take the importance of indirect pathways for information flows seriously (Ahuja 2000). In unreported sensitivity analyses we find that the effects of degree and betweeness measures are qualitatively the same. Despite the availability of more complex, weighted centrality measures (such as information or flow centrality), we choose betweeness for its ready interpretability. Biases may be introduced as firms at the center of small stars, unconnected to the main component, that will have higher betweeness scores. Such biases work against our arguments about the relative importance of membership and position, however. We thank Phil Bonacich for a conversation reminding us of the benefits of simplicity in network measures.

[13]We use R&D ties to minimize collinearity among network measures for Boston. Such ties also represent the most intensive involvement of for-profit organizational forms in nonproprietary research.

[14]Using application date rather than issue date is common practice in literatures relating to patents as it represents the best measure of the time when patentable research was actually completed while avoiding numerous methodological issues raised by the lags between patent filing and issue (Hall et al. 2000). Modeling patents in this fashion allows us to assume a simultaneous (with the same year) effect of network ties on patents and thus also limits the possibility of reverse causality. Nevertheless, regressions run in a two-stage least squares framework find no evidence of reciprocal causality from patents to ties.

[15]This robust effect is net of both direct R&D ties to local Boston PROs and local measures of betweeness centrality in Model 6. In unreported sensitivity analyses, we tested the possibility that our "membership" variable actually proxies for a distinction between isolated DBFs and organizations with ties (whether connected or unconnected to the main component) by including a variable indicating whether organizations were true isolates or simply connected to smaller network components in the region. We found no effect of connections to smaller regional components. The relevant distinction then is between

being linked to or isolated from the largest weakly connected component in the region.

[16]Note that the separation of our 11-year time frame into two periods corresponds with the beginning of increasing volatility and growth in DBF membership in the local component and a period of steep decline in the component's reliance on PRO ties. See Figure 3.

[17]This finding is not inconsistent with research demonstrating that networks rich in structural holes hinder patent in industries characterized by high patent rates (Walker et al. 1997, Ahuja 2000). Our findings, however, suggest a further question about the role that different organizational forms play in mediating the effects of network characteristics on information flows.

[18]We thank an anonymous reviewer whose questions about the substitutability of channel and conduit ties in innovation networks greatly aided our thinking.

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