Knowledge Networks in the Boston Biotechnology Community

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Abstract

We examine the consequences of geographic location and network position on patenting by biotechnology firms in the Boston metropolitan area. Using ten years of data on firm-level collaborative alliances and patenting, we construct measures of network position both within and outside the Boston region to test the effects of geographically bounded social networks on innovation. We find that the cohesiveness of the Boston biotechnology community greatly increases with the diversity of organizational participants, the addition of geographically distant partners, and the maturity of the industry. Using fixed-effects, negative binomial models on a pooled cross-section of network and patenting data, we demonstrate that within the Boston region any connection to the main network component positively effects firm patenting. In contrast, when innovation networks include geographically distant partners, a more central position in the network yields positive returns to innovation. Likewise, a diverse portfolio of partners aids firm patenting in physically dispersed networks but hinders it in a regionally bounded innovation network.

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1. Introduction.

The U.S. biotechnology industry exemplifies many of the general features of science-based sectors. Biotechnology firms in the U.S. and Europe are clustered in a small number of geographic regions and are strongly dependent upon public research organizations, such as universities, for skilled labor and novel scientific competencies (Zucker, Darby & Brewer 1998; Anselin, Varga & Acs 1997; Audretsch & Stephan 1996). These firms are embedded in multiple networks of strategic alliances and gain competitive advantage from continuous scientific and technical innovation (Powell, Koput & Smith-Doerr 1996).

Spatial agglomeration is an important feature of biotechnology as R&D efforts spill over within industries and regions (Jaffe 1986). These spillovers are an important source of increasing returns and growth (Romer 1986; Krugman 1991), and provide the underpinning for examinations of knowledge production that fall under the broad heading of the new economic geography (David & Rosenbloom 1990; Glaeser et al 1992; Jaffe et al 1993; Audretsch & Feldman 1996; Feldman & Audretsch 1999). The geographic clustering of biotechnology firms provides internal benefits in the form of both a highly skilled labor force and access to the research of 'star' academic scientists (Krugman 1991; Zucker & Darby 1996), as well as external benefits generated by the local diffusion of new knowledge that is not easily appropriated by outsiders. The idea that knowledge is highly clustered regionally and shared within a technological community builds upon Marshall's (1920) writings on industrial districts. Indeed, in a handful of key biotech clusters (e.g. SF Bay, Boston, San Diego), the secrets of the industry may truly be "in the air" (Marshall 1920).

But access to new knowledge and capabilities in biotechnology also occurs through strategic alliance networks that are national and international in their reach (Powell 1996; Liebeskind et. al. 1996; Walker, Shan & Kogut 1997). In addition to being located in physical communities, successful biotechnology firms are positioned in a social structural landscape distinct from their geographic location. Centrality in these innovation networks increases firm performance by increasing rates of learning and enhancing access to resources and new sources of knowledge (Powell et. al 1996). For economic sociologists, networks are regarded as the "plumbing" of the market through which information and resources flow (Burt, 1992; Podolny, 2001). Thus, alongside the information benefits of location in a regional cluster, biotechnology firms garner increasing returns to innovation through both local and trans-local network connections. Moreover, the cohesiveness of networks within regional clusters depends strongly on the inclusion of physically distant partners (Owen-Smith, Riccaboni, Pammolli & Powell 2002). External linkages are critical to both sustaining a dense local network and reducing the risk of ossification in such closely knit communities.

Consequently, geographic propinquity and network centrality represent substantively different locations in a field where the ability to innovate determines survival. Our task in this paper is to analyze the differential effects of these two types of 'position' on the development of new knowledge. One aspect of this question involves the diversity of organizations located in different regions. Biotechnology is a field where all of the relevant capabilities are seldom found under a single organizational roof. The field had its origins in university labs, where research was supported by substantial government investments in R&D. As the field developed, universities, nonprofit research centers, major research hospitals, and start-up firms all had a hand in moving the 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 focused methods of drug discovery (Malerba & Orsenigo 2001). Nowhere do we find all these types of organizations located in physical proximity, so the maturation of the industry involved reaching out across clusters to access resources.

These diverse participants represent more than novel combinations of organizations, however. As Nelson (1981, 1986) argued in his work on the varied institutions that support technical advance, progress on an R&D frontier is highly dependent on public organizations that operate in very different selection environments from for-profit firms. The mix of organizational forms involved in biotechnology may well be one reason for its rapid emergence. We suspect that the combination of the responsiveness of private firms and the dedicated resources of public organizations was crucial to the generation of novel technologies. In a provocative passage in his *Politics and Markets*, Lindblom (1977) argued that the market system resembled a hand with all fingers but no thumbs, while a centralized planning economy was all thumbs, but no fingers. A key part of our analytical task is to sort out the divergent roles played by public and private organizations in biotechnology's emergence.

We begin to address these issues by analyzing 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. Our approach is distinguished by the use of novel social network visualization techniques and quantitative measures of network position in two networks defined by the geographic location of partners. We first introduce the Boston region -- highlighting both the scale of biotechnology activity and the diversity of organizational forms and selection environments in the area. Boston is perhaps the toughest case in which to find network effects on innovation, net of co-location. The next section describes our visualization techniques and presents several network images, along with a discussion of the descriptive properties of those networks. We then present an overview of our data, methods and models. Section five discusses findings regarding the effects of propinquity and centrality on firm level patent outcomes. Section six reports additional results from models that include measures of network diversity and reliance on public research organizations. Our conclusions and ideas about future research are presented in the final section.

2. Why Boston?

We examine the relationship between local and trans-local network position and patent volume for dedicated biotechnology firms (hereafter, DBFs) located in the Boston area. The Boston metropolitan area is home to one of the largest concentrations of biotechnology firms in the world. In addition to DBFs, Boston boasts an exceptionally large and diverse population of public research organizations (hereafter, PROs). PROs are research-intensive, non-governmental organizations that are not driven by a profit motivation. We include in this group both 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 can be found in the Boston region. The co-location 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[1], nonprofit, private, large and small) coincides with an equally diverse set of selection environments, and represents a local organizational field or knowledge community (Powell 1996).

Boston, then, is a strong candidate for a geographic region where information could diffuse locally in a thriving technological community. Because PROs are primarily focused on academic research, and produce public science, they may be 'leakier' types of organizations than firms, thus their diversity and number may increase the geographically localized spillovers generated by 'basic' life-science research. Likewise, Boston area venture capital firms are much more likely to invest locally than are firms in other regions (Powell et al 2002). This type of ecology is the kind of environment where firms might see innovation benefits from spatial agglomeration independent of their embeddedness in trans-local strategic alliance networks. In order to examine the differential effects of local and trans-local networks, we draw on a relational database (coded from *Bioscan*) that captures twelve years (1988-1999) of network ties involving DBF and partner organizations (VCs and PROs) located in the Boston Metro area.[2]

3. Network visualization of the Boston biotechnology community.

Defining the networks. We focus on the differential effects on patent volume of geographically localized and trans-local centrality, hence we develop two different networks involving Boston-based organizations. The first network, which we dub

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[1] While both government agencies (e.g. the National Institutes of Health) and public universities might be considered 'public,' we differentiate them and assign such agencies to the category 'Government.' No such agencies are located in the Boston region.

[2] For details on the Bioscan database from which the Boston data are derived, see Powell et. al. 1996: 124-29; Powell et. al. 1999: 136-140; Owen-Smith et. al. 2002.

'Boston,' contains only organizations located in the region and the ties among them. In this data set there are 58 DBFs, 19 PROs, and 37 VC firms. We observe 201 formal contractual relationships. These connections include R&D partnerships, licensing deals, joint assignment of patents, commercialization and marketing agreements, and investment ties among these 114 organizations during the period 1988-1999.

The second network, which we label 'Boston +,' comprises all organizations of any type in all locations that ever have a network tie to a Boston-based organization. The Boston + network, then, represents the location of Boston-area DBFs in a global network without reference to the physical location of partners. The Boston + network includes 212 DBFs, 96 PROs, 240 VC firms, 24 Government agencies, and 168 Pharmaceutical/Chemical/Healthcare companies.[3] We observe 1,559 ties among these 740 organizations during the period 1988-1999. This latter network includes all organizations and ties in the smaller local network.

Network visualization in Pajek. We draw on novel methodological techniques to develop meaningful visual representations of these two networks. Pajek (Slovenian for 'spider') is a freeware package for the analysis and visualization of large network data sets.[4] Pajek includes a set of network drawing algorithms based on both graph theoretic conceptions of distance in a network and the physical theory of random fields (Guyon 1994). These

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[3] The Boston + network is more diverse in terms of organizational forms than the Boston network because neither Government agencies nor large pharmaceutical/chemical/healthcare companies (such as Merck or Eli Lilly) are located in the Boston metropolitan area. Indeed very few of either of these sorts of organizations are located in *any* of the established biotechnology clusters in the U.S.

[4] Pajek was developed by Vladimir Batagelj and Andrej Mrvar and is available online at http://vlado.fmf.uni-lj.si/pub/networks/pajek/ . Pajek has been used in diverse fields to represent complex network data (Albert, Jeong, & Barabasi 2000; Batagelj & Mrvar 2000; Owen-Smith et. al. 2002; White & Harary 2001).

minimum energy or 'spring-embedded'-network-drawing algorithms permit us to accurately represent social network data in two-dimensional Euclidean space.

The two algorithms we use simulate our collaboration network as a system of interacting particles. Organizational nodes are assumed to repel each other while network ties are represented as 'springs' that draw connected nodes closer together. Spring embedded algorithms iteratively locate a representation of the network that minimizes the overall 'energy' of the system. In these representations, Euclidean distances among nodes are generated by the pattern of ties connecting the entire network.

We draw first on the Fruchterman-Reingold (FR) algorithm (1991), which optimizes network images without reference to the graph theoretic distance among nodes, to develop initial positions for all organizations (connected and unconnected). We then turn to a second algorithm, the Kamada-Kawai (KK) (1989), to reposition the connected nodes in the network. Where the FR algorithm positions all nodes by analogy to a physical system, the KK algorithm locates connected nodes adjacent to one another and makes Euclidean distances among nodes proportional to graph theoretic distances. In other words, the KK algorithm visually represents a system where the distance between nodes is a function of the shortest network path between them. Taken together, these two algorithms generate substantively significant visual representations of networks, which place isolated organizations on the periphery of the image while capturing the pattern and density of collaborative activity and reflecting the extent to which such collaborations generate meaningful clusters of organizations.

Images of Boston. Figure 1 presents a series of images of the Boston network in 1988. The shape of the nodes in these images reflects organizational type (triangles = PROS, circles = DBFs, squares = venture capital firms, diamonds = pharmaceutical/chemical/healthcare firms).

[Figure 1 here]

Note several interesting features of Figure 1. First, consider the Boston network at the upper left. In 1988 this network is relatively sparse, with the bulk of Boston area organizations isolated from the network of formal relationships.[5] 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 the earliest year of our network data, then, the Boston biotechnology community is 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 upon key public research organizations. Removing these organizations from the network results in the complete collapse of the component.

Figure 2 represents the Boston + network in 1988. Notice first that this network is both larger and much more organizationally diverse than the Boston network due to the inclusion of government agencies (represented by brown triangles) and large pharmaceuticals (represented by diamonds). The complete Boston + network in the upper

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[5] Recall that isolates are positioned on the periphery of the image by the FR algorithm.

left quadrant of Figure 2 is also strikingly different visually. Where the Boston-only network is a sparse corridor reliant upon 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 DBFs. 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.

[Figure 2 here]

The great majority of the 182 organizations connected to this component have only one network tie. In order to visually explore the cohesiveness of this network, we remove all organizations that have fewer than two ties from the component. The resulting image is more densely and redundantly bonded than the local main component. Note that this network is dependent for its cohesiveness on two distinct types of organizations. In order 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 suggests 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 VC firms and large companies from outside the region reach in and attach to Boston-area DBFs. These outside ties also altered the composition of the main component, reducing its structural dependence upon local PROs. Nevertheless, this increased network robustness may well have come at the expense of open information flow. Large pharmaceutical companies and PROs put research results and intellectual property to very different uses.

Figure 3 is a reprise of Figure 1, presenting a series of images of the Boston network at the end of our time period in 1998. Note that a large number of Boston-based organizations remain isolated from the main component of the network despite its increased size and diversity. By 1998, more than 58% of Boston DBFs were connected to this component. The structural characteristics of the component have changed, as local biotech firms began working directly with one another rather than forming 'chains' through PROs. Local VC firms also play a much more active role in the network, which is notably apparent in the portion of the corridor to the right of MIT. The Boston network in 1998 is still anchored by PROs (particularly MIT, BU, Harvard, and Brigham and Women's Hospital), but that reliance is decreasing as is evidenced by the image of the component with PROs and their network connections removed.

[Figure 3 here]

Consider the final frame of Figure 3, which illustrates that nearly 30% of Boston DBFs remain connected in a component that does not rely on public organizations. Indeed, the growth of direct biotech-to-biotech ties and the 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 one held by large companies in the trans-local network.

Figure 4 reflects the Boston + network in 1998. The main component of the network has grown larger, including more than twice the number of organizations connected to the 1988 core, and more densely connected. This component now includes nearly 78% of Boston DBFs. In network terms, then, the community of Boston DBFs is much more cohesive when non-Boston organizations are included in the network. As with Figure 2, we remove organizations with only a single tie in order to more clearly visualize the structure of the network core. Like the Boston network, Boston + has also evolved markedly. Where its main component was contingent on both PROs and large firms for cohesiveness in 1988, the growing role of external (largely California) VC firms has reduced this reliance. Unlike in 1988 when removing both PROs and large firms dissolved the network, such an extraction in 1998 leaves a connected component of more than 100 DBFs and VCs that includes fully 60% of our focal Boston-area firms.

[Figure 4 here]

Figures one through four graphically represent a number of key features of innovation networks involving Boston-based organizations. First, geographically localized networks are less densely and redundantly attached and much more firmly anchored by PROs than are trans-local networks. A significant proportion of local biotechnology firms are part of the main component of both networks, but overall cohesiveness (in terms of network reachability) among Boston DBFs increases with time, with growing organizational diversity in the type of partner, and with the inclusion of partner organizations from outside the region.

Finally, the Boston and Boston + networks differ on significant structural dimensions. The local network is deeply dependent for its coherence on PROs through the late 1990s. Even in the early years, the trans-local network remains connected, requiring both PROs and large firms to be removed to 'unyoke' the network. By 1998, external VC firms add to the robustness of this network. These innovation networks manifest distinct structural characteristics depending on whether or not they are geographically bounded, suggesting the possibility that similar positions in these networks may yield substantially divergent benefits to firms.

Two possibilities are immediately apparent. First, position in the Boston network may be unimportant as geographically localized informal knowledge spillovers reduce the need for firms to seek resources and novel information through formal network connections. The effectiveness of the local community may be conditioned by common norms and conventions that guide the transmission of information. Consequently, centrality in alliance networks within the region would matter little for innovation. In the more trans-local network, however, centrality matters a great deal because knowledge diffuses over physical distances primarily through formal connections to well-situated partners.

Moreover, Boston's reliance on PROs may limit the importance of centrality because these organizations pursue public science (Dasgupta & David 1987), and more effectively 'broadcast' new findings within a region. In the Boston + network, however, the institutional diversity of structurally important organizations may result in a situation where network ties more strongly channel knowledge diffusion for specific rather than general-purpose uses. For-profit partners, such as VCs and large corporations, support private science and hence strive to limit spillovers in order to appropriate novel knowledge to speed proprietary development of new technologies. In addition to the effects of physical distance, the distribution of types of organizations that connect networks may result in differential effects of network centrality on innovation. We now turn to negative binomial models of a 10-year pooled-cross section of firm-level patent data in order to explore the question of how variation in network positions influences R&D productivity.

4. Models and Methods

Network Variables. Four social network measures derived from Boston and Boston + provide our primary independent variables for this analysis. The first, which we call *membership*, is a dummy variable set to one if a firm is connected to the main component of the network. The main component (recall figures 1-4) in a social network is the largest group of nodes (in this case organizations) that can reach each other through network paths. *Membership* indicates whether or not a firm has the potential to search for information and resources through a network without reflecting differential positions within that network.

Our second variable, *position*, is an indicator of a firm's network centrality based on Freeman's (1977, 1979) measure of betweenness.[6] This measure captures the extent

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[6] 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 will have extremely high betweeness scores.

to which firms sit astride network pathways between other organizations. Betweenness centrality indicates a firm's ability to absorb (or interrupt) information flows through networks. Where *membership* indicates whether or not a firm has any capabilities to collect information through network connections, *position* distinguishes among levels of ability by appeal to structural position in the network.

The two remaining network variables, *partner diversity,* and *percent public* reflect two aspects of a firm's network portfolio. The first variable is a dummy variable set to one if a firm connects to multiple types of organizations (two or more partner types in Boston, four or more in Boston +). The second variable is simply the proportion of a firm's total ties that link to PROs. We construct each of these variables separately for the Boston and Boston + networks.

Control variables. We also introduce a variety of control variables into the models. These include a dummy variable indicating whether a firm is publicly traded in a given year, age and a quadratic age term in years, the size of a firm (operationalized as the log of the number of a firm's employees), and a lagged patent count variable to limit the effects of serial auto-correlation in our pooled cross-section. All models are also estimated with fixed firm and year effects to control for unobserved heterogeneity across organizations and time. Table 1 summarizes our variables and presents basic descriptive statistics. Appendix Table 1 presents bi-variate correlations.

[Table 1 here]

However, such biases work against a strong positive effect of betweeness on patenting. We thank Phil Bonancich for a conversation reminding us of the benefits of simplicy in network measures.

Model specification. We model counts of issued patents[7] in a ten year (1990-99) pooled cross-section, using a negative binomial specification (Hausman, Hall, & Griliches 1984; Cameron & Tivendi 1998) to correct for over-dispersion in patent counts. Our independent and control variables are uniformly lagged by two years to accommodate the median (25 month) delay from filing to issue of patents. Using a fixed-effects specification for firm and year controls with a lagged dependent variable, we model the dependent variable ($y_{i,t}$) as

$$y_{i,t} = \alpha_i + \delta_t + \lambda(y_{i,t-2}) + \sum_{j=1}^{J} \beta_j (x_{i,t-2,j}) + \varepsilon_{i,t}$$

Where α_i is the effect of DBF i $(i=1,\ldots N)$, δ_t is the effect of year t $(t = 1, \ldots 10)$, and β_j is the within firm slope for x_j pooled over all firms and years.

5. Findings.

Propinquity and Centrality. We first analyze the differential effects of network position and membership in the Boston and Boston + networks. Table 2 reports findings from these models.

[Table 2 here]

Model 1 includes all our control variables and finds (not surprisingly) significant effects of firm size, age, and the quadratic age term on later patent volume, suggesting

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[7] Despite findings to the effect that application date is a better estimator of value (Hall, Jaffe, & Trajtenberg 2000), we opt to model patents by issue date with lagged independent variables for several reasons. Our key independent variables extend to 1999. Because of significant right censoring involved in modeling patents by application date, we opt to shift the burden of the lag to our independent variables. Hence we estimate models on a pool from 1990-1999 to accommodate a two-year lag in our network variables. As a result, our findings are more relevant to discussions of the volume of a firm's innovations rather than the market value of an IP portfolio.

diminishing returns to age. Models 2-6 report a number of nested specifications with network position and membership variables calculated from the Boston and Boston + networks. Models two and three include only network measures from Boston and highlight the extent to which formal collaborative ties *within* an established geographic cluster influence innovative output. Note the positive and significant effect of a connection to the network main component (membership) net of position within the network (centrality) in Model 3. The implication here is that, within a geographic community, a looser, more diffuse conception of network membership positively effects innovation by biotechnology firms. Within the local Boston area, any capacity to appropriate information spillovers through networks yields innovation benefits above mere geographic co-location, but where an organization sits in a local network has no significant effect.

Models 4 and 5 test the effects on patenting of membership and position in the larger, more organizationally diverse, and physically diffuse Boston + network. Here, the results show the opposite pattern from the Boston network, a strongly positive effect of network centrality and no significant effect of membership. Trans-locally, then, firms garner returns to innovation from being better positioned to appropriate knowledge flows channeled through a network rather than from having the basic capacity to search through them.

Model six combines network variables for Boston and Boston +, finding that the different dynamics of local and trans-local networks are robust. Again membership matters locally, while centrality looms large trans-locally. Additionally, we find a marginally significant negative effect of membership in the Boston + network, suggesting that a weak connection to such a physically dispersed network may actually hinder a firm's attempts to innovation. Put colloquially, this is akin to a competent minor leaguer trying to play in the majors while lacking the necessary skills and resources. Where local membership represents an entry ticket to information-rich networks anchored by PROs, trans-local membership reflects a weak connection to a large network that driven more by commercial approaches to innovation and knowledge dissemination.

Our key findings are best described by returning to the plumbing imagery common in the network literature. Consider these networks as pipes through which information can flow. In the Boston area, any connection to the system of network pipes yields positive returns, while being situated at the nexus of multiple flows (a high betweenness centrality score) does not generate additional benefits, possibly because additional connections result in redundant information. In contrast, being peripherally connected to the network system in the Boston + network yields no benefits and may even hinder attempts to innovate as information and resources may trickle in slowly. But being situated at the intersection of numerous external flows of information and resources enhances a firm's knowledge outputs. Several different mechanisms underpin these findings.

In Boston, a connection to the main component serves as an entry ticket to informal networks of academic and industrial scientists. In other words, any organizational tie signals membership in a technological community where information flows primarily through informal individual channels. Membership alone is sufficient for access to the 'codes' for exchanging knowledge. Additionally, the predominant role of PROs in both the Boston region and network results in 'leakier' network pipes because of strong institutional commitments to academic styles of research and reporting,. In other words, information spills out of local pipes resulting in broad diffusion within a network component, rather than the point-to-point transmission that typifies more focused and proprietary organization-to-organization ties.

A different pattern holds, we argue, for the Boston + network. Physical distance limits the viability of individual-level networks and local codes are rarely shared externally, hence organizational diversity and multiple pathways among participants alter the dynamics of knowledge transmission. To take the plumbing analogy one step further, consider a system where information and resource pipelines run through multiple channels. In this metaphor, network ties are pipelines, and channels reflect the different types of organizations through which those pathways flow. In Boston, for instance, where the great majority of structurally important pathways flow through PROs, there is a single important channel. In the Boston + network, however, there are at least two and possibly three different channels,[8] through PROs, pharmaceuticals and VCs. In this more elaborate network, returns to centrality will be increased to the extent that DBFs are located astride multiple channels and numerous pipelines. A position astride multiple pipelines in a unitary channel would be characterized by a high degree of centrality and relative homogeneity of partners (for instance a biotech firm that sat astride multiple pathways through PROs). In contrast, a central position in multiple channels would involve both high centrality and high diversity (for instance a firm located at the intersection of pathways through VCs, pharmaceuticals, and PROs). Our second set of models begins to examine these possibilities.

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[8] We expect small VC firms and large pharmaceutical firms to manifest important differences with regard to the development and control of information. Nevertheless, it may be more apt to speak at a higher level of generality about 'academic' and 'private sector' channels for knowledge flows.

Diversity and PRO ties. We draw on relatively simple measures to capture the diversity of a DBF's partners (*Partner Diversity*) and the degree of DBF reliance on ties to PROs (*Percent Public*). These measures allow us to untangle the effects of connections to diverse institutional channels from structural centrality in network pipelines. Table 3 presents models that suggest an interesting relationship between partner diversity and biotechnology innovation.

[Table 3 here]

The models reported in Table three relate characteristics of a firm's collaborative portfolio and position in the network to the volume of its patents. Consider model one, which reports findings for the Boston network alone. The significant effect of network membership on patenting is robust to the inclusion of diversity and public reliance measures. But the addition of those measures increases the magnitude of both the membership and the position effect above that reported in Table 2. Nevertheless, this model's contribution can be found in the significant negative relationship between multiple partner types and later patenting. Note also the positive, though non-significant, effect of greater reliance on PRO partnerships.

Model 1 illuminates a local network dynamic focused on a single, structurally important type of partner, the PRO. The negative effect of partner diversity may reflect the mismatch between market-oriented approaches to R&D and the institutional rules of a community dominated by academic research organizations. DBF connections to for-profit organizations, such as local VC firms, may trigger conflicts between innovation styles and regimes of information disclosure, thus differentially benefiting firms whose partners come from only one side of the aisle.

Model 2 presents findings from the Boston + network and, as was the case in Boston, highlights the importance of partner diversity for DBF patenting. While including diversity and public reliance measures from the local network increases the magnitude of membership and position effects, in the context of Boston + the same measures decrease coefficient strength and limit the significance of the centrality effect on patenting.[9] The diminished role of centrality is accompanied by a strong positive effect of partner diversity and a marginally significant negative relationship between reliance on PRO ties and patenting. Here we see dual evidence of the importance of diversity for innovation in a geographically dispersed network. Having ties to multiple partners yields a positive benefit, while (net of that effect) a high proportion of ties to a single type of organization (PROs) is marginally detrimental to innovation. An organizationally diverse portfolio of partners, we argue, enables firms to more effectively navigate in a network where key participants exhibit divergent institutional commitments to open information flow. Under such conditions, relying heavily on ties to a single type of organizational partner, especially to a partner committed to broad dissemination of knowledge, hinders firm patenting. In networks dominated by multiple forms of organization, emphasizing ties to PROs may limit a DBF's ability to collect new information through more market-oriented institutional channels as for-profit partners may opt to avoid sharing information through 'leaky' networks.

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[9] A high level of partner diversity, in this case ties to at least four of the five types of organizations that populate the Boston + network, is only correlated at about the .20 level with local network position (See Appendix table 1).

The effect of a variety of network measures on biotechnology patenting varies with the geographic location of partners. This pattern is apparent for both a firm's location in the network (membership and centrality) and the composition of its collaborative portfolio (partner diversity and public sector reliance). Any connection to the main network corridor in Boston increases DBF patenting, but only a central position in the network yields a similar effect in Boston +. In the same vein, an organizationally diverse group of partners hinders DBF patenting locally, while comparable diversity yields positive returns in the larger trans-local network.[10]

Network effects on biotechnology patenting in the Boston region are conditioned by both the system's structural dependence upon multiple organizational forms and by the geographic location of nodes. Networks anchored by a single type of organization may require alternative strategies on the part of science-based firms relative to networks that are redundantly connected. In addition, formal collaborative networks internal to a regional cluster affect innovation differently than otherwise similar, but geographically diffuse, networks. These patterns may result, in part, from regional externalities generated by spillovers from intensive public sector R&D efforts.

Model 3 combines measures from both networks. Here, observed effects of Boston + measures are actually trans-local as they are net of the effects of Boston-only measures. Network effects in Boston (Model 1) are robust to the inclusion of trans-local variables. The Boston + coefficients, however, are altered in this combined model. Notice the resurgence of the Boston + centrality effect, and the lessened significance of both partner diversity and public sector reliance from Model 2 to Model 3. These changes

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[10] The effects of partner diversity, position, and membership in these networks appear to be independent. In models not reported here we tested the effects of multiplicative interactions between our diversity measure and both membership and centrality, finding the interaction terms to be uniformly non-significant.

imply shifting dynamics across geographically diffuse networks that contain local ties and similar networks that are bounded to exclude them.

When taking partner diversity into account, trans-local centrality exerts a stronger effect when local measures are included, suggesting that location in a thriving regional community could, because of geographically localized spillovers, limit the need for firms to be centrally positioned in an external network. In other words, information flows to centrally connected DBFs through the Boston + network and then diffuses to less connected firms that are geographic neighbors. The physical proximity of Boston-area DBFs enables them to partake of local externalities and thus reduces their need to be centrally positioned in a network of partners that are not neighbors.

Interpreted in light of the structural variations we find across the Boston and Boston + networks, the dynamics we observe stem from divergent styles of information search, diverse institutional commitments, and the overlapping geographic and social structural positions of organizations. These complex network forces are best understood in the context of several interesting lines of work that examine the relationship between public and private science and the interdependence of multiple types of organizations at the frontiers of a science-based industry.

6. Conclusions and Implications.

Two major theoretical puzzles motivate our analyses. We began with a concern for the distinct conceptions of location emphasized by economic geographers (position in a geographic region) and economic sociologists (position in a social network). Geographically clustered Boston-area biotech firms benefit from connections to local collaborative networks and a greater number of those firms become reachable through network channels as geographically distant and organizationally varied partners are added to the mix.

That extra connectivity comes at cost, however, as the trans-local network only aids DBF innovators to the extent that they are well positioned astride multiple network 'pipelines.' We also find that a broad set of partners hinders innovation in a local network anchored by public research organizations, but similar breadth increases patenting by firms that are well situated in the physically dispersed network. This important relationship between multiple conceptions of position, on the one hand, and levels of organizational diversity, on the other has significant implications for firms in an industry characterized by a fast-moving research frontier with strong reliance on knowledge developed in multiple selection environments under divergent sets of institutional rules.

We argue that variations in organizational form have two key implications for studying innovation networks. First, public, private, and non-profit organizations exist in distinct selection environments. This simple insight suggests that social networks anchored by many different forms of organization will be robust to both error and attack (Albert, Jeong, & Barabasi, 2000). Diversely anchored networks are less likely to dissolve than those that rely on a single type of organization for their cohesiveness. By the same token, networks centered on public research organizations will be more stable than networks centered on firms simply because universities and research institutes are much less subject to selection pressures than for-profit entities. Variations in selection environments also generate alternative strategies by which organizations extract benefits from their collaborative ties. Hence, organizationally heterogeneous networks are likely to be characterized by conflicting styles of information search.

Along the same lines, organizational diversity across academic and market-oriented regimes entails different institutional commitments to norms of information disclosure and use (Dasgupta & David 1987, 1994). Organizations with a greater focus on pursuing private science for pecuniary gain will necessarily be less efficacious 'broadcasters' of new knowledge than will organizations committed to public science and open information flow following a more 'academic' model. In our view, PROs and various types of firms will differ not only in their selection pressures and strategies, but also in the extent to which they serve as sources for the broad diffusion of novel information. The extent and character of information spillovers in both high-technology regions and geographically dispersed innovation networks, then, will vary with the distribution of types of organizations involved in R&D, as some nodes in networks and members of communities are 'leakier' than others.

These issues of public and private science are closely linked to the empirical setting of the biotechnology industry, where DBFs achieve advantage on a fast-moving research frontier through continual innovation (Powell et al 1996). Because no single organization (or even single type of organization) maintains the range of scientific and organizational capacities necessary to discover, develop, and market new therapeutics internally, diverse collaborations are the rule in both commercial and academic life science (Powell & Owen-Smith 1998, 2002). For a science-based biotechnology firm, the ability to successfully innovate is conditioned by both internal capabilities and external access to information and resources. In this industry, firm-level success is a function of having both the internal absorptive capacity (Cohen & Levinthal, 1989, 1990) necessary to develop and evaluate research and the external connections that provide access to new knowledge and resources. In more prosaic terms, successful biotechnology firms must be able to make news in order to successfully consume it (Nelson 1990). Whether the 'news' itself flows to a firm through formal networks or more diffuse and geographically localized spillovers is unimportant. Nevertheless, the joint efforts of public and private organizations may be necessary to enable the creation of any news at all on an R&D frontier (Rosenberg & Nelson 1994).

Regardless of the conception of position, a high degree of organizational diversity seems to be a necessary condition for innovation in this complex collaborative field. At the firm level, however, the apparent necessity of matching internal capacities with external connections to very different types of partners may be a double-edged sword. We argue that a key distinction between the local Boston network and its trans-local counterpart has to do with the systems' varying levels of structural reliance on multiple types of organizations.

One reason for the importance of centrality in the Boston + network is that it enhances firms' ability to search for information and resources along multiple network pipelines. But our finding with regards to partner diversity complicates the nature of search through networks as such diversity reflects both variant selection environments and institutional approaches to knowledge use among partners. In the language we have adopted, positive returns to sitting astride multiple network pipelines may be rendered more problematic when firms must search through multiple institutional 'channels.'

Divergent institutional rules for developing and sharing information require successful firms to develop not only the internal scientific capacities necessary to produce and evaluate cutting-edge research, but also the organizational procedures and competencies necessary to enable 'multi-vocal' action in potentially contradictory institutional regimes. The capacity to contribute to cutting-edge basic science, orchestrate clinical trials in research hospitals, and collaborate with large multinational firms in the distribution and sale of an initial product requires a small firm to engage with very different audiences. But the development of such competencies can also hinder firms' efforts to garner information and resources in more organizationally homogeneous settings, as evidenced by our finding of a negative effect of partner diversity on innovation in the PRO dominated Boston region.

Consider Henderson's (1994) finding that large pharmaceutical firms engaged in cardiovascular drug discovery efforts benefited from advances in the new biotechnology more quickly when they allowed their scientists to publish and thus form connections to tacademic researchers. These firms gained an advantage in commercial drug development by participating simultaneously in the worlds of public and private science. Similarly, Boston-area DBFs are more effective patentors to the extent that they can play both commercial and academic "games," while developing new knowledge in a community dominated by PROs and a trans-local network anchored by both commercial and academic entities. In both these examples, firms paradoxically gain proprietary benefits by acting in accordance with a set of institutional rules that are more oriented toward open information flow.

We expect that successfully navigating through local communities and global networks interpenetrated by distinct institutional rule sets raises sizeable coordination issues for the firms and universities at the research frontier. On the one hand, firms benefit from being well positioned in organizationally diverse networks, but producing research in such collaborative webs means sharing potentially valuable knowledge through networks that have a high number of 'leaky' nodes. The strong presence of public research institutions in this field, then, is simultaneously a necessary condition for innovation and a potential threat to a firm's ability to appropriate returns to its R&D programs.

On the flip side of the coin, universities benefit from connections to the network to the extent that being well positioned allows them to leverage their research capacities, intellectual property, and expertise into resources and access to proprietary information (Owen-Smith & Powell 2001a, 2001b). But patents are the entry ticket to such deals for both firms and universities (Powell et. al. 1999; Owen-Smith, 2000) and the patenting of certain sorts of information, for instance research tools, may be detrimental to the pursuit of basic research as the exclusivity offered by intellectual property rights may create a "tragedy of the anti-commons" (Heller & Eisenberg, 1998).

Understanding the effects of network position on both commercial and academic R&D in the life sciences, then, depends on considering the joint effects of multiple conceptions of location, divergent institutional commitments, and networks that span distinctive selection environments upon the activities and outcomes of firm and university R&D. We recognize that the Boston area represents a single case of a regional community embedded in a physically dispersed formal network. Nevertheless, our findings are suggestive of the need for further comparative examination across regions at different stages of maturation and with different initial distributions of public, private, and non-profit participants.

More generally, though, we contend that the analyses of high technology clusters must be undertaken with a concern for both organizational diversity and disparate conceptions of location. Knowledge spillovers that promote innovation may diffuse more effectively within regional clusters than outside of them (because of the local existence of informal networks). But, we contend, more than simple physical distance is at work in the divergent dynamics of the Boston and Boston + networks. In trans-local innovation networks, knowledge flows occur more through network pipelines than through diffuse 'broadcasts' from neighboring organizations. More importantly, the character of those knowledge flows is conditioned by the structural dependence of such networks upon a complex mix of public, private, and non-profit organizational forms. This mixture is a necessary condition for any innovation in this quickly evolving science-driven field. But that very necessity alters the styles of search organizations use to extract information and resources from their networks and neighbors, and presents significant coordination problems for successful organizations who must maintain multiple and potentially conflicting identities to innovate successfully in a diverse and multiply embedded community.

Table 1. Variable Summary

VARIABLE	DEFINITION	MEAN	SD
Patents	(DV) Yearly count of issued patents	3.174	4.845
Lagged Patents	Yearly count of issued patents, two year lag	1.924	3.197
Public	Dummy variable, 1= publicly traded firm		
Age	Age in years since firm founding	8.506	4.645
Age^2	Age in years since firm founding, squared	93.859	100.380
Log(size)	Log(number of employees)	4.401	1.047
Boston Membership	Dummy variable, 1=connected to the main network component in Boston network.		
Boston + Membership	Dummy variable, 1=connected to the main component in the Boston + network		
Local Position	DBF betweenness centrality score, Boston Network	.007	.016
Trans-local Position	DBF betweenness centrality score, Boston + Network	.021	.020
Local Percent Public	Percentage of firm network connections to PROs, Boston Network	.336	.417
Trans-local percent public	Percentage of firm network connections to PROs, Boston + network	.196	.219
Local Partner Diversity	Dummy variable, 1=firm with two or more partner types, Boston Network		
Trans-local partner diversity	Dummy variable, 1=firm with four or more partner types, Boston + network		

Table 2. Position and Membership: Negative Binomial Models of Patent Counts for Boston Area DBFs, 1991-1999.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Controls						
Public (SE)	.041 (.181)	.098 (.178)	.121 (.182)	.058 (.185)	.047 (.183)	.055 (.178)
Age	2.237* (.440)	1.977* (.442)	2.013* (.446)	2.268* (.449)	1.798* (.478)	1.503* (.478)
Age^2	-.012* (.003)	-.012* (.003)	-.011* (.002)	-.012* (.003)	-.011* (.003)	-.011* (.003)
Log(Size)	.481* (.114)	.445* (.112)	.451* (.112)	.472* (.116)	.459* (.114)	.435* (.110)
Lagged Pats	.002 (.013)	.014 (.014)	.012 (.014)	.003 (.014)	-.002 (.014)	.008 (.013)
Boston						
Membership		.353* (.105)	.336* (.108)			.392* (.107)
Position			2.042 (3.142)			-1.557 (3.315)
Boston +						
Membership				-.304 (.451)	-.532 (.446)	-.717$^+$ (.438)
Position					12.046* (4.087)	13.150* (4.202)
Pseudo-R^2	.307	.309	.310	.302	.308	.317
LR Chi-sq	470.26	460.43	460.85	450.14	458.72	471.50
N	335	330	330	330	330	330

All models include fixed firm and year effects
All independent and control variables lagged two years
+ $p<.10$
* $p<.05$

Table 3. Diversity and Public Partners: Negative Binomial Models of Patent Counts for Boston Area DBFs, 1991-1999

	Model 1	Model 2	Model 3
Controls			
Public (SE)	.247 (.187)	.030 (.181)	.173 (.184)
Age	1.883* (.441)	1.703* (.475)	1.384* (.474)
Age^2	-.012* (.003)	-.010* (.003)	-.011* (.003)
Log(Size)	.406* (.110)	.459* (.112)	.389* (.108)
Lagged Pats	.005 (.013)	-.004 (.014)	.001 (.014)
Boston			
Membership	.443* (.116)		.497* (.117)
Position	4.224 (3.127)		.189 (3.431)
Multiple partner types	-.408* (.129)		-.367* (.127)
Percent ties to public	.052 (.168)		-.117 (.180)
Boston +			
Membership		-.391 (.450)	-.629 (.439)
Position		8.406^{+} 4.571	9.629* (4.626)
Multiple partner types		.279* (.130)	.209^{+} (.124)
Percent ties to public		-.676^{+} (.376)	-.505 (.359)
Pseudo-R^2	.316	.312	.324
LR Chi-sq	468.75	463.97	481.39
N	328	329	328

All independent and control variables lagged two years

All models include fixed firm and year effects

+ p<.10

* p<.05

Table A.1: Correlation Matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Patents	1.0000													
2. Lagpats	0.6150	1.0000												
3. Public	0.2232	0.2622	1.0000											
4. Age	0.1925	0.3298	0.1860	1.0000										
5. Agesq	0.1575	0.2742	0.0716	0.9549	1.0000									
6. Logsize	0.4940	0.4627	0.5059	0.3533	0.2490	1.0000								
7. B+parts	0.2478	0.2284	0.2267	0.1356	0.0325	0.3224	1.0000							
8. Bosparts	-0.0324	-0.0590	0.0510	0.0114	-0.0448	0.1074	0.2384	1.0000						
9. Bospubl	-0.0630	-0.0205	0.1498	-0.0006	-0.0574	0.0631	0.2322	0.1634	1.0000					
10. B+publ	-0.0965	-0.0638	0.0248	0.0214	-0.0070	-0.0160	0.2397	0.1759	0.3581	1.0000				
11. Bosmemb	0.2199	0.1130	0.1532	0.0704	0.0194	0.2496	0.2598	0.3416	0.5739	0.1726	1.0000			
12. Bospos	0.1051	0.0980	0.0223	0.0913	0.0430	0.1774	0.1571	0.4438	0.2445	0.0717	0.4352	1.0000		
13 B+memb	0.1316	0.0951	0.2591	-0.0976	-0.1986	0.2410	0.2071	0.1832	0.2558	0.2488	0.3078	0.1418	1.0000	
14. B+pos	0.2836	0.2967	0.2580	0.1322	0.0381	0.4610	0.6267	0.4232	0.2537	0.0789	0.3871	0.2971	0.3330	1.0000

Figure 1. Boston Network, 1988

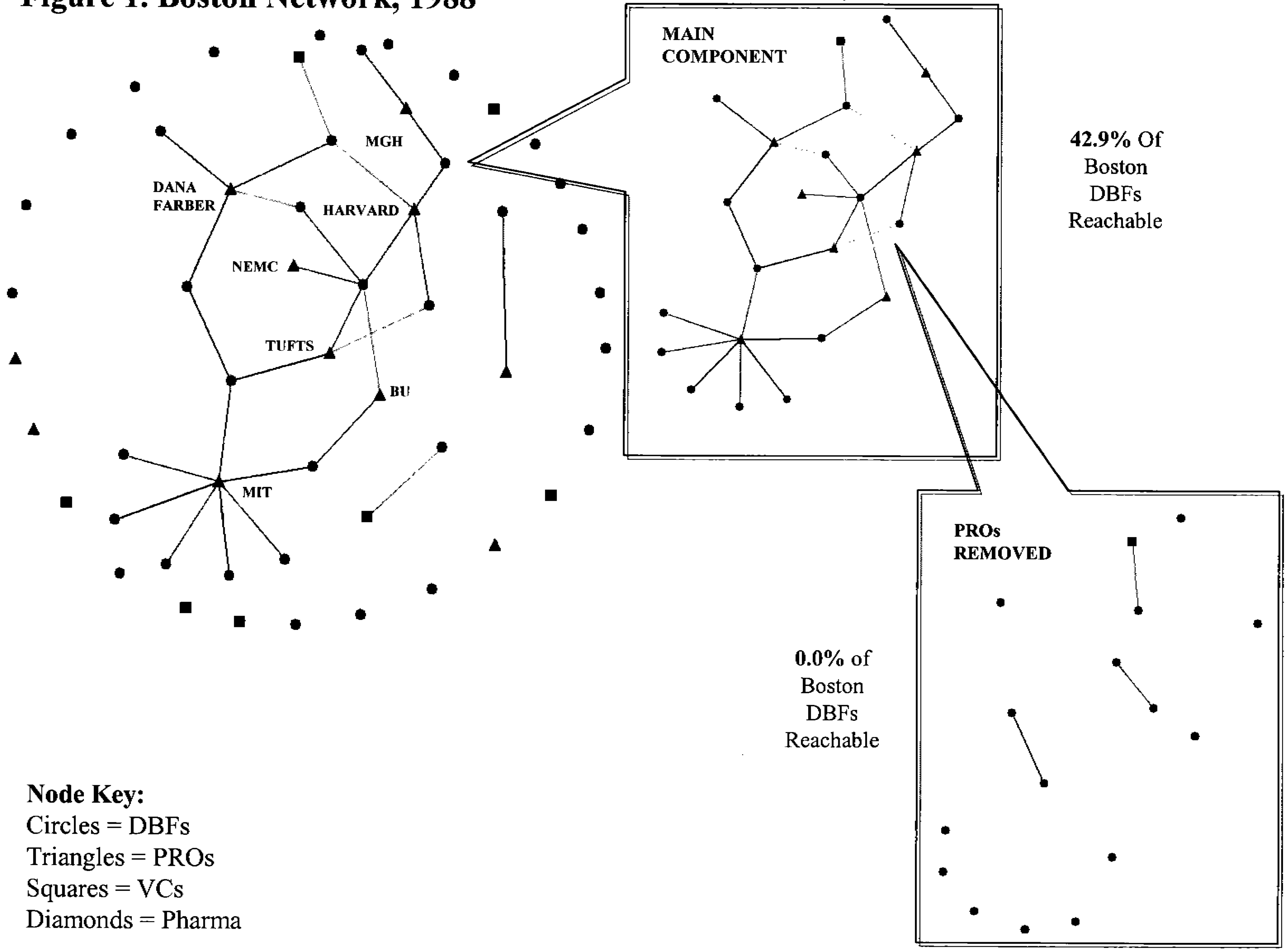
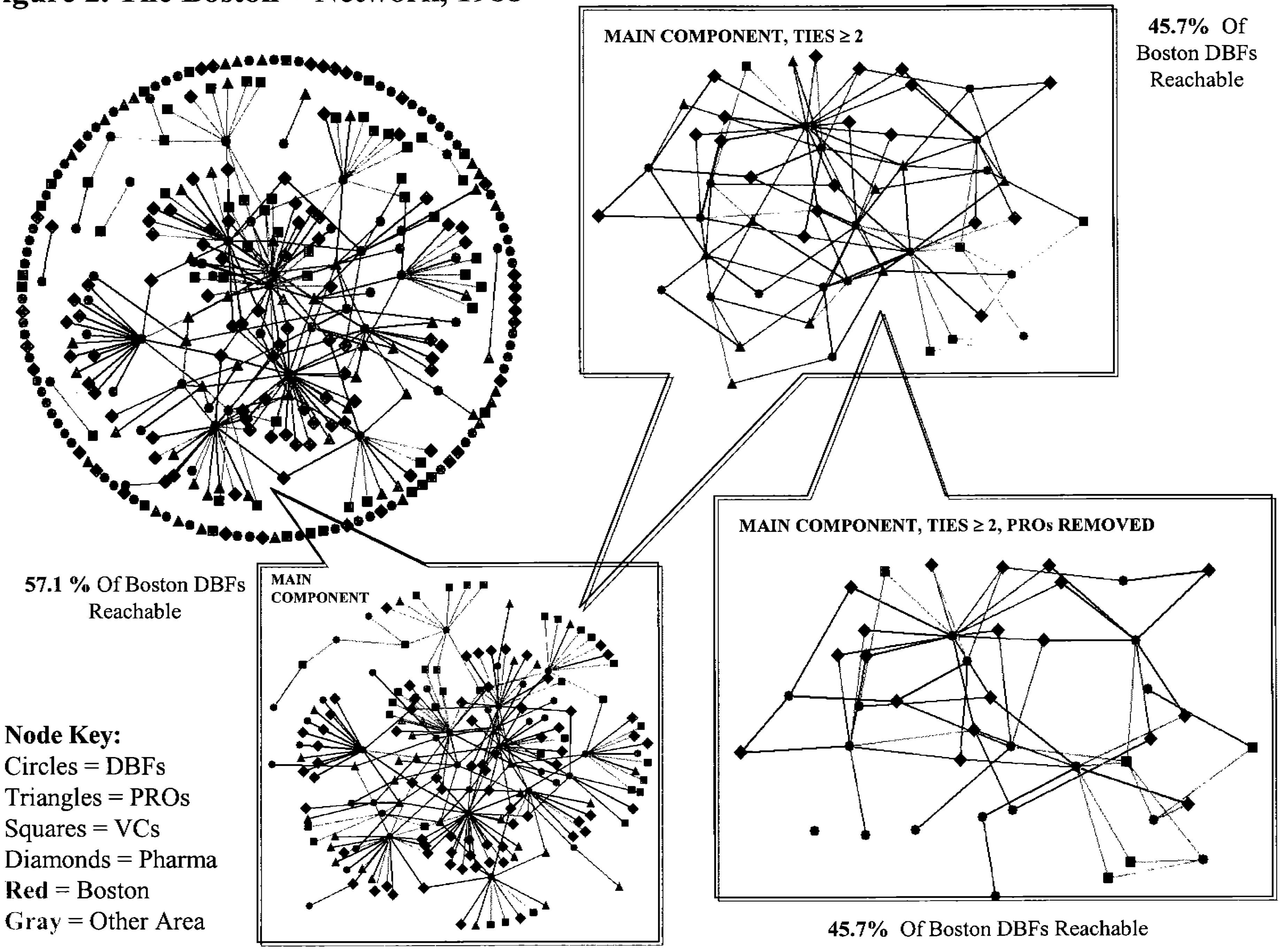


Figure 2. The Boston + Network, 1988



MAIN COMPONENT, TIES ≥ 2

45.7% Of Boston DBFs Reachable

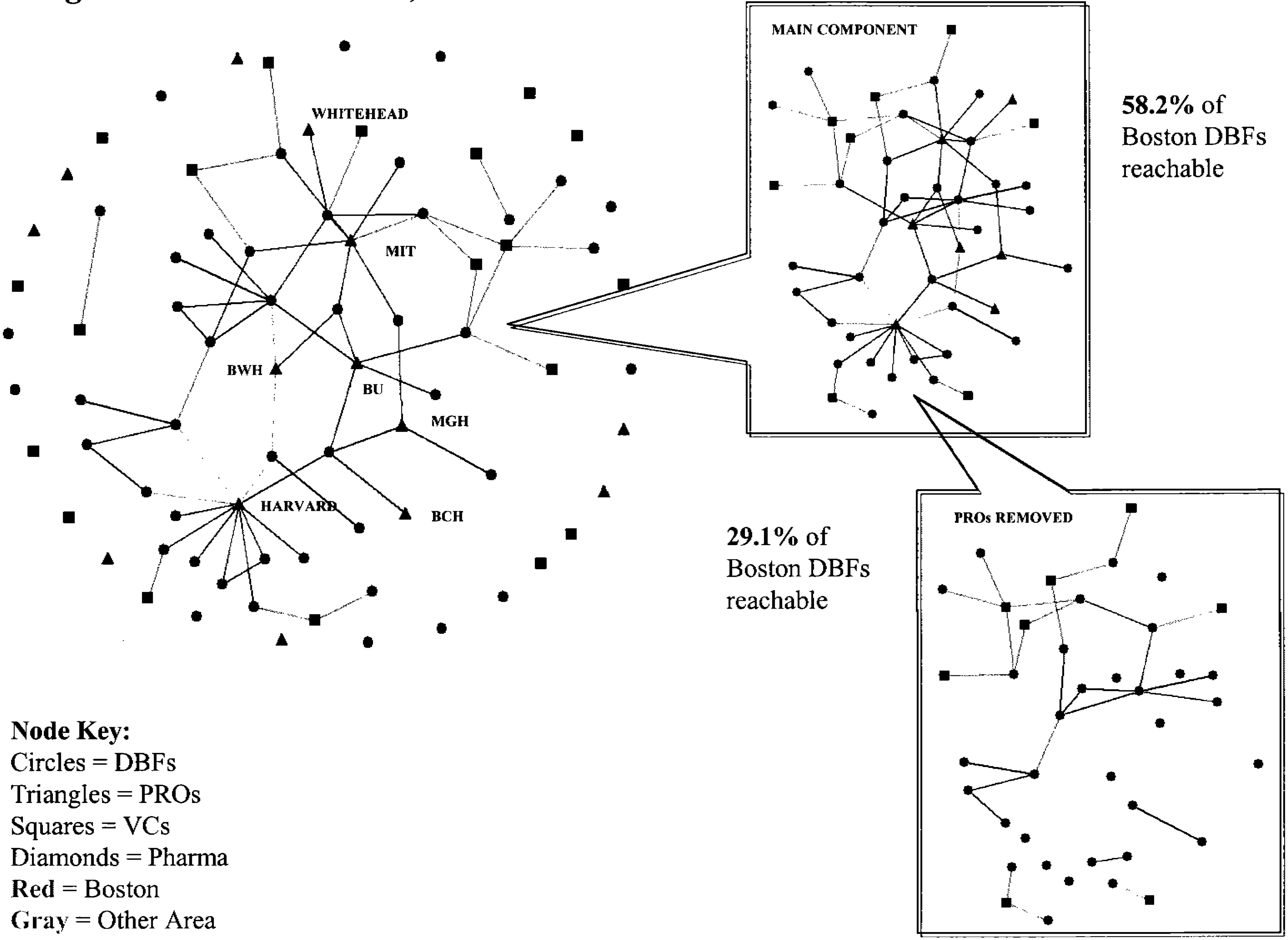
57.1 % Of Boston DBFs Reachable

MAIN COMPONENT

MAIN COMPONENT, TIES ≥ 2, PROs REMOVED

45.7% Of Boston DBFs Reachable

Figure 3. Boston Network, 1998

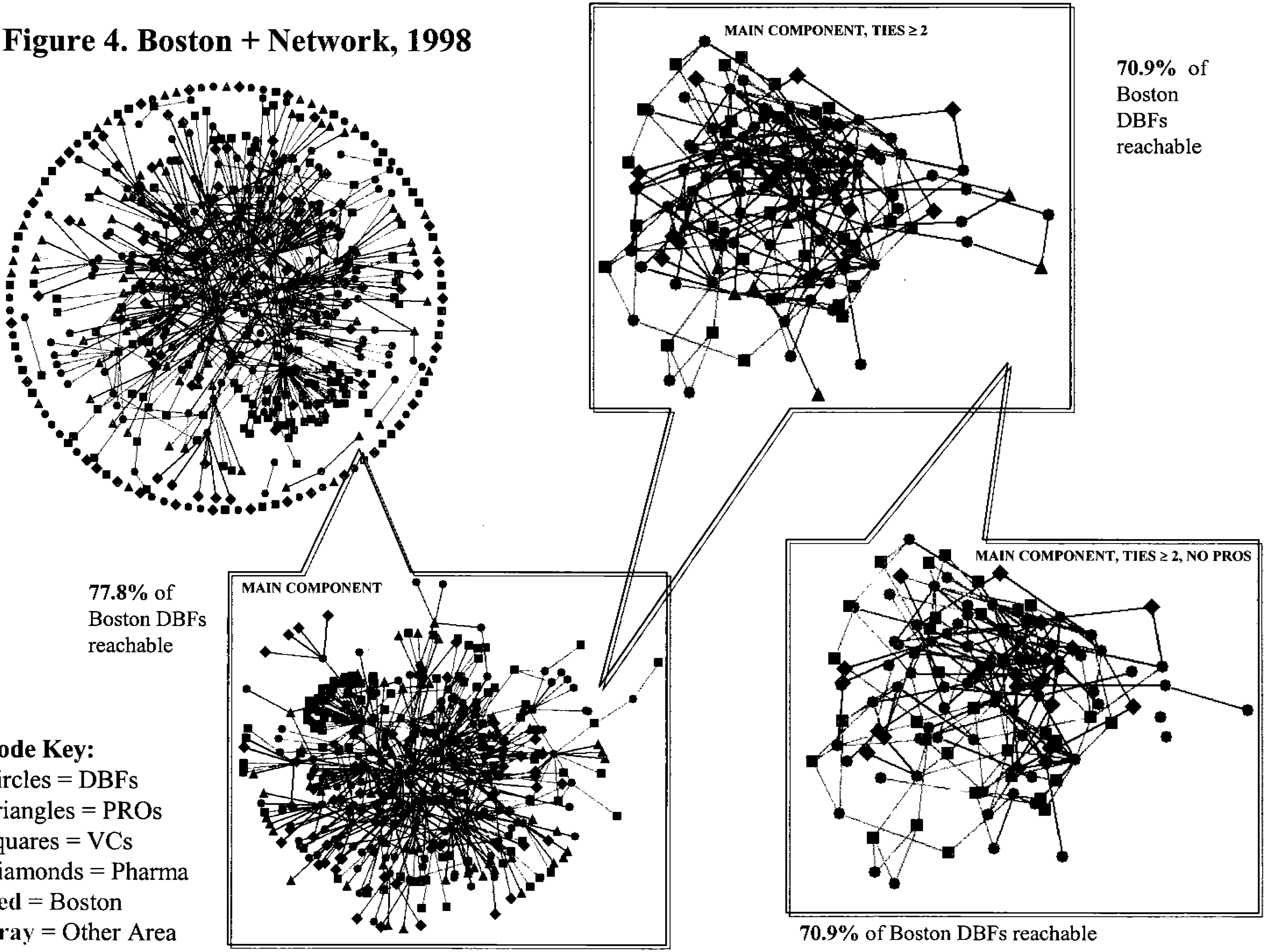


58.2% of Boston DBFs reachable

29.1% of Boston DBFs reachable

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

Figure 4. Boston + Network, 1998



70.9% of
Boston
DBFs
reachable

77.8% of
Boston DBFs
reachable

70.9% of Boston DBFs reachable

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

References.

Albert R., H. Jeong, and A. Barabasi, 2000. Error and Attack Tolerance in Complex Networks. ***Nature*** **406** 378-382

Anselin, L, A Varga, and Z Acs, 1997. Local Geographic Spillovers between University Research and High Technology Innovations. **J. Urban Economics 42** 422-448.

Audretsch, D. and M. Feldman, 1996. Knowledge Spillovers and the Geography of Innovation and Production. **Am. Economic Rev. 86** 630-640.

Audretsch, D. and P. Stephan, 1996. Company-Scientist Locational Links: The Case of Biotechnology. **Am. Econ. Rev. 86** 641-652.

Batagelj V., A. Mrvar. 2000. Drawing Genealogies. ***Connections*** **21** 47-57.

Burt, R.S. 1992. *Structural Holes: The Social Structure of Competition.* Cambridge, MA: Harvard University Press.

Cameron, A. C. and P. K. Trivendi, 1998. *Regression Analysis of Count Data.* Cambridge, UK: Cambridge University Press.

Cohen, W. and D. Levinthal, 1989. Innovation and Learning: The Two Faces of R&D. **Economic Journal 99** 569-596.

-----, 1990. Absorptive Capacity: A New Perspective on Learning and Innovation. **Admin. Sci. Quart. 35** 128-252.

Dasgupta, P. and P. David, 1987. Information Disclosure and the Economics of Science and Technology. in G.R. Feiwel (ed.) *Arrow and the Ascent of Modern Economic Theory*. New York: New York University Press. Pp. 519-542.

----- 1994. Toward a New Economics of Science. **Research Policy 23** 487-521.

P. David & J. Rosenbloom, 1990. Marshallian Factor Market Externalities and the Dynamics of Industrial Localization. **J. Urban Economics 28** 349-370.

Feldman, M. and D. Audretsch, 1999. Innovation in Cities: Science-Based Diversity, Specialization, and Localized Monopoly. **Eur. Econ. Rev. 43** 409-429.

Freeman, L.C., 1977. A Set of Measures of Centrality Based on Betweenness. **Sociometry 40** 35-41.

-----, 1979. Centrality in Social Networks: Conceptual Clarification. **Soc. Networks 1** 215-239.

Fruchterman, T., E. Reingold. 1991. Graph Drawing by Force-Directed Replacement. ***Software -- Practice and Experience*** **21** 1129-1164.

Glaeser E.L., H.D. Kallal, J.A.Scheinkman, and A. Schleifer. 1992. Growth in Cities. **J.**

Polit. Econ. 100 1126-1152.

Guyon X., 1994. *Random Fields on a Network.* Berlin, Springer.
Hall, B.H., A. Jaffe, and M. Trajtenberg, 2000. Patent Citations and Market Value: A First Look. **NBER Working Paper #7741.**

Hausman, J. B.H. Hall, and Z. Griliches, 1984. Econometric Models for Count Data With an Application to the Patents R&D Relationship, **Econometrica 52** 909-938.

Heller, M. & R. S. Eisenberg, 1998. Can Patents Deter Innovation: The Anticommons in Biomedical Research. **Science 280** 698-701.

Henderson, R. 1994. The Evolution of Integrative Capacity: Innovation in Cardiovascular Drug Discovery. **Ind. Corp. Change 3** 607-630.

Jaffe, A. 1986. Technological Opportunity and Spillovers of R&D: Evidence From Firms' Patents, Profits, and Market Value. **Am. Econ. Rev. 76** 984-1001.

Jaffe, A. M. Trajtenberg, and R. Henderson, 1993. Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations. **Quart. J. Econ. 63** 577-598.

Kamada, T. and S.-Kawai, 1989. An Algorithm for Drawing General Undirected Graphs. **Inform. Process. Lett. 31** 7-15.

Krugman, P. 1991. Increasing Returns and Economic Geography. **J. Polit. Econ. 99** 483-499.

Liebeskind, J., A. Oliver, L. Zucker, M. Brewer. 1996. Social Networks, Learning, and Flexibility: Sourcing Scientific Knowledge in New Biotechnology Firms. ***Org. Sci.* 7** 428-443.

Lindblom, C.E. 1977. *Politics and Markets: The World's Political Economic Systems.* New York: Basic Books.

F. Malerba and L. Orsenigo, 2001. Innovation and Market Structure in the Dynamics of the Pharmaceutical Industry and Biotechnology: Toward a History Friendly Model. **CESPRI Working Paper**

Marshall, A. 1920. *Industry and Trade.* London: U.K.: Macmillan.

Nelson, R.R. 1981. Assessing Private Enterprise: An Exegesis of Tangled Doctrine. **Bell J. Econ. 12**93-111.
-----, 1986. Institutions Supporting Technical Advance in Industry. **Am. Econ. Rev. 76** 186-189.

-----, 1990. Capitalism as an Engine of Progress. **Res Policy 19** 193-214.

Owen-Smith, J. 2000. *Public Science, Private Science: The Causes and Consequences of Patenting by Research One Universities."* Ph.D. Dissertation, University of Arizona.

Owen-Smith J. and W. W. Powell, 2001a. To Patent or Not: Faculty Decisions and Institutional Success at Technology Transfer. **J. Tech. Transfer 26** 99-114.

------, 2001b. Careers and Contradictions: Faculty Responses to the Transformation of Knowledge and Its Uses in the Life Sciences. Pp 109-140 in Vallas, S. P. (ed.) *The Transformation of Work.* New York: JAI 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 Sci.** Forthcoming.

Podolny, J. 2001. Networks as the Pipes and Prisms of the Market. **Amer. J. Sociology 107** 33-60.

Powell, W. W. 1996. Inter-Organizational Collaboration in the Biotechnology Industry. **J. Inst. And Theoretical Econ. 152** 197-215.

Powell, W. W., K. Koput, and L. Smith-Doerr, 1996. Interorganization Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology. **Admin. Sci. Quart. 41** 116-145.

Powell, W.W. K.W. Koput, L. Smith-Doerr, and J. Owen-Smith, 1999. Network Position and Firm Performance: Organizational Returns to Collaboration in the Biotechnology Industry. in Andrews, S. & D. Knoke (eds.) *Networks in and Around Organizations* Greenwich, CT: JAI Press.

Powell, W.W. and J. Owen-Smith, 1998. Universities and the Market for Intellectual Property in the Life Sciences. **J. Policy Analysis and Management. 17** 253-277

-----, 2002. The New World of Knowledge Production in the Life Sciences. Forthcoming in S. Brint (ed.) *The Future of the City of the Intellect: The Changing American University.* Stanford, CA: Stanford University Press.

Powell, W.W., K.W. Koput, J. Bowie, and L. Smith-Doerr, 2002. The Spatial Clustering of Science and Capital. **J. Reg. Studies Forthcoming.**

Romer, P.M. 1986. Increasing Returns and Long Run Growth. **J. Polit. Econ. 94** 1002-1037.

Rosenberg, N. & R. R. Nelson, 1994. American Universities and Technical Advance in Industry. **Research Policy 23** 323-348.

Walker G. B. Kogut, and W.J. Shan, 1997. Social Capital, Structural Holes, and the Formation of an Industry Network. **Organ. Sci. 8** 109-125.

White, D. R. and F. Harary, 2001. The Cohesiveness of Blocks in Social Networks: Node Connectivity and Conditional Density. **Soc. Meth. 31**, 305-359.

Zucker L.G. and M. Darby, 1996. Star Scientists and Institutional Transformation: Patterns of Invention and Innovation in the Formation of the Biotechnology Industry. **P. Natl. Acad. Sci. 93** 12709-12716.

Zucker, L.G., M.R. Darby, M.B. Brewer. 1997. Intellectual Human Capital and the Birth of U.S. Biotechnology Enterprises. ***Amer. Econ. Rev.*** **88** 290-306.